1
Introduction

Pneumatic structures are membrane structures that are stabilized by tension due to the applied internal pressures. These structures exhibit interesting characteristics from a structural viewpoint, such as a reduced self-weight, which results in structures that are globally lighter and more economical than conventional ones. Pneumatic structures also have some characteristics that contribute to sustainable development, such as their reusability and the use of natural lighting and ventilation.

Although pneumatic structures have been in use for the past 30 years, there is much to be developed and researched particularly regarding the employed materials, because new materials are being produced for developing pneumatic structures with better strength and durability.

1.1
Membrane structures

Unlike conventional structures, membrane structures are used as shelter constructions because of one of their important characteristics: their self–weight.

Otto[1] defines a membrane as a flexible skin stretched in such a way that it is subjected to tension. Mixed structures that combine traction cables with elements working under compression or bending-compression are also lightweight structure solutions.

Simple membrane structures such as tents were used as shelter about 40,000 years ago and then were used for transitory activities such as military campaigns and circus presentations. Because of their easy assembly, tents is also an option for shelter in emergency situations due to natural hazards, such as floods and hurricanes, or even in war.

Nowadays, aspects related to environment preservation and sustainable development are being determined by the design of engineering solutions. Membrane structures have some characteristics that contribute to sustainable development, such as the use of natural light and ventilation and its possibility of reuse. It is also shown that this type of structure enables architectonic flexibility and the search for better structural efficiency.

Wakefield [2] has reported that the design of lightweight membrane structures requires a special approach. As opposed to wood, concrete, and iron structures, in the case of membrane structures, loads are transfered to the supports by the forces in the structure membrane. Wakefield [2] has reported that these structures undergo significant displacements when loaded. Therefore, the analysis of this type of structure must consider the onset of large displacements and therefore a nonlinear structural response.

Lightweight structures are regarded by Bletzinger [3] as the proper structures for optimal material use under extreme load or pretension conditions, i. e., for maximizing the material efficiency under the imposed constraints.

1.2
Pneumatic structures

According to Dent [4] pneumatic structures refer to structures acted on by air or gas and relate particularly to architecture and construction.

Marcipar et al. [5] defines that pneumatic structures are composed by an exterior flexible membrane that contains a fluid inside (in general air or helium). The function of the interior fluid is to maintain the exterior membrane under tension. The final shape of the inflatable structure and its structural resistance depend strongly of the deformation of the external membrane, the loads, and the pattern design. The stiffness of the membrane is directly related to the pressure of the air contained inside the structure and the internal volume.

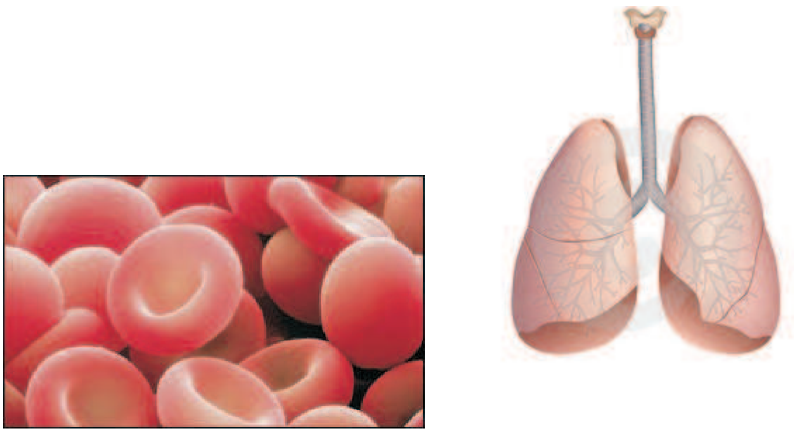
This type of structure has some advantages: with larger volumes and higher pressures greater spans can be achieved. Furthermore, the pneumatic structures can be erected or dismantled quickly, are light, portable and reduced material use. It therefore offers a possible solution to a wide range of problems, both of social and commercial kinds. For instance, pneumatic constructions can be used to overcome temporary shortages of warehousing space. It can also be used to provide shelter for the homeless in times of natural or man-made disaster, and in these early days of space exploration, it has even been suggested for lunar shelters. But of more importance than these applications demonstrate, is the fact that pneumatic construction points the way to an architectural revolution. To correct the environmental deficiencies of rigid traditional structural envelopes, energy must be supplied to heat and ventilate them, bringing them up to the comfort standards that are determined by the building’s function; the amount of this applied energy depends on the insulation characteristics of the structural envelope. The properties and the different shapes of pneumatic structures are described in the work of Herzog [6]. Parameters to determine the final shape of these structures are: type of loading, magnitude of internal pressure, type of boundary conditions, formation of the membrane, number of membranes, type of utilization, type of membrane material, surface curvature, etc.

Pneumatic structures are classified on the basis of the pressure applied, as high– or low–pressure pneumatic structures. A sub-category of pneumatic structures is defined on the basis of their construction operation: air–controlled construction, air–stabilized construction, and inflated cushions. In civil engineering, air–stabilized constructions and inflated cushions are employed. Air–stabilized constructions, as the name suggests, are membrane structures supported by pressure differentials. Inflated cushions are closed membrane structures having an internal pressure.

1.2.1
Air–stabilised construction

This is a thin flexible membrane which is supported solely by pressure differentials. These differences in pressure induce tensile stresses into the membrane (Dent [4]).

The air–supported structure is made up of four elements according to Dent [4]: the structural membrane, the means of supporting this membrane, the means of anchoring it to the ground, and the means of access in and out of the building structure. The membrane structure is fabricated using fabrics or foils and it is supported by a pressure differential maintained by a constant supply of air provided by simple low pressure fans. The membrane is generally clamped firmly to a concrete foundation. Air locks are necessary for ease of access against the pressure differential.



(a) (b)

Figure 1.1: Pneumatic structures in man's body: (a) Red blood cells, (b) lung

Pneumatic structures can be found in nature like flexible membranes containing fluids under pressure. Some examples in human body are the red blood cells (figure 1.1(a)) and the lung (figure 1.1(b)). Another example found in nature is the flower calceolaria that is a flower with inflated petals and it is shown in figure 1.2.

Figure 1.2: Calceolaria - Inflated flower

Animal skin was used for water storage and for construction of tents as shelters. The first attempt to use air pressure in membranes was probably the sail. Due to wind, the differences in pressure cause inflation of the sail providing a mean of propulsion.

A more recent pneumatic structure development is the balloon, which was created in 1709 by the brazilian Bartolomeu Lourenço de Gusmão (Visoni and Canalle [7]). Dent [4] reports the use of the balloon as air transportation system in eighteenth century. In 1783 the Montgolfier brothers inflated, with hot air a 10 m diameter sphere made of paper and linen, and they observed this sphere rise to a considerable height before it descended. At the same time as these experiments of the Montgolfiers, Jean Baptiste Meusnier was suggesting a design for a dirigible non-rigid airship, which was even more revolutionary. His designs were for a cigar shaped structure with an inner bag, containing hydrogen as the lifting agent, surrounded by an outer envelope containing air at a higher pressure than that of the atmosphere.

According to Dent [4] in one field pneumatic construction has established itself as the best solution to a particular problem, that of providing motor vehicles with a smoother ride. Its main advantages over the solid tire are twofold, firstly, its superior ability to absorb road shocks through considerably greater deformation, and secondly its unrivaled handling characteristics due to the fact that a greater surface area of tire is in contact with the road surface.

The way that air pressure is used to prestress the membrane distinguishes two types of pneumatic structures: low–pressure and high–pressure.

1.2.2
High–pressure inflatable structures

This type of inflatable structure is inflated with high pressure, usually higher than $1.0kN/m^2$. According to Kröplin [8] the high–pressure inflatable structures require the used of reinforced membrane materials. Motro [9] reports that the low–pressure pneumatic structures occur when the whole functional space is pressurized to the extent required to balance the external applied load. The full structure size is active and hence structural efficiency is extremely high. Because a substantial uplift acts on the membrane, it has to be anchored to the ground or weighted down along the boundary. Additional architectural drawbacks of this system stem from the need for the enclosed space to be essentially sealed and for air to be pumped continuously, thus limiting architectural flexibility and range of applications.

Marcipar et al. [5] reported that the use of inflated elements with high–pressure has often been proposed, but they have rarely been built. One example is the Fuji-Pavillon in Japan. The reasons are that the necessary materials, structural design and manufacturing techniques have not yet been fully developed. There are also some disadvantages, such as joints design and execution and their big vulnerability to air losses. In general, high–pressure inflated structures are difficult to maintain and repair and have a high cost.

1.2.3
Low–pressure inflatable structures

Low–pressure inflated structures are the most common type used by civil engineering constructions. Some advantages of this type of structures are described by Marcipar et al. [5]. 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 a constant low internal pressure to account for the air losses through the material pores and the seams.

Kröplin [8] reports that in the case of low pressure, about $0.5kN/m^2$, an open wall can be used, whereby the pressure is permanently imposed by a blower, which is capable to erect the structure.

1.2.4
Inflated cushions

Inflated cushions are composed by two or more membranes closed and pressurized, with no accessible interior. Rigid elements at the edges or compression rings are required in this structure to give form and to close the envelopes. An example of this rigid elements are shown in figure 1.3(c). Figure 1.3(a) is an example of an ETFE cushions façade and a testing of full-scale mock-up is presented in Figure 1.3(b).

(a) (b) (c)

Figure 1.3: Inflated cushions (a) 3-D overview of irregular shaped ETFE cushions used in facade assembly (source: Watts [10]), (b) Testing of full-scale mock-ups (source: LeCuyer [11]), and (c) Rigid edge detail (source: Watts [10])

Gómez-González et al. [12] reported that although this type of structure first experienced an important development in the sixties and seventies, it is in the last decade that the inflatable system have improved most, allowing new sustainable strategies in climatic adaptive envelopes.

The probable reason for the increasing membranes use in constructions is due to the improvement of new materials with higher resistance and durability.

The study of Gómez-González et al. [12] also shows the geographical situation of these structures. It is concluded that 40% of the studied projects have been made in Germany or United Kingdom, where these systems have been more accurately researched and manufactured. Also, the climatic conditions of these areas, with solar radiation gains in the winter and mild temperatures in the summer, benefit the application of these systems. However, in the last decade the use of this technology has been developed in other zones with more extreme summers, like south Europe or some regions in Asia.

Marcipar et al. [5] reported that these structures are used instead of glass elements due to their lower price, which is 1/3 of a glass covering. So far there are only two German companies dealing with these inflated cushions in the world market.

1.2.5 Pneumatic constructions

The first known architectural attempt to apply the balloon principle to earth-bound structures was projected by the English engineer, Frederick William Lanchester (Dent [4]). In his patent of 1917 for a field hospital, the basic principles of air supported construction for buildings were realized. This patent, clearly derived from balloon and airship construction, is remarkable on two accounts: firstly, he appears to be fully aware of all the basic implications of buildings supported by air, and secondly, although his patent concerns a field hospital, he mentions the potential of air supported buildings for huge spans such as those encountered in air craft hangars and sports arena.

The pneumatic camping structure appeared before the Second World War consisting of a waterproof membrane stretched between a pair of intersection air inflated ribs, exemplifying a very feasible form of construction for portable buildings (Dent [4]).

The first air supported building rose in 1946 in the U.S.A. to shelter antennae from the severe climatic conditions: the Distant Early Warning (DEW) line, a "fence" of radars in the Arctic that would guard against Soviet bomber attacks. It continues to this day as the North Warning System, presented by the newer radome on the left in Figure 1.4.

Figure 1.4: Distant Early Warning (DEW) line (source: Canadian military journal [13])

According to Dent [4] of prime importance to the whole project for the radomes were the Laboratory wind tunnel tests, which analyzed the stresses induced in the membrane by wind loads. In association with this research, membrane materials were developed which were able to withstand severe exposure. These consisted of strong man-made fibers, such as nylon or terylene, which were covered with a synthetic coating of vinyl, neoprene or hypalon. As Lanchester had predicted, a pressure differential of only 70mm of water pressure was all that was required to maintain the rigidity of these 15 m diameter radomes in winds of up to 240 km/h. By the mid 1950's, the successful performance of these radomes in the extreme climate of the northern frontier of America had proved the practicality of pneumatic structures.

In the last years the pneumatic structures has improved in conjunction with the membrane materials and it has been used for temporary or permanent use. An example of temporary use is a low pressure inflatable structure for conferences and an example of permanent use is a stadium with inflated cushions as Allianz Arena (Figure 1.5).

Figure 1.5: Allianz Arena in Munich

In Brazil, some companies construct pneumatic structures that are mainly air–stabilized constructions. The material used in this type of construction is generally fabric. Inflated cushions have several advantages and are the most widely developed type of pneumatic structure in the last 10 years. Despite the technological developments and advantages of this type of structure, inflated cushions can be found mainly in Europe, and only a few constructions are found outside Europe. One example is the water cube in Beijing, which was constructed for the Olympics in 2008.

The study of Majorana et al. [14] investigated the numerical and physical models developed for the design of a membrane roof for the Baptist Church of Fortaleza as well as the fabrication and construction of the actual membrane; the results of the models were compared with those of the real structure. The roof area amounted to about 2,900 m^2, which is a national record for flexible border membranes, and to the best of the author's knowledge, this roof is the first case of a fully computer assisted design process within Brazil.

The motivation for pursuing this topic goes beyond the advantages of lightweight structures, which are mentioned earlier. The lack of inflated cushions in Brazil and their limited use in other countries of the American continent are motivations for research on this topic. The global distribution of pneumatic structures using inflated cushions, particularly using ethylene tetrafluoroethylene (ETFE) material, is shown in figure 1.6.

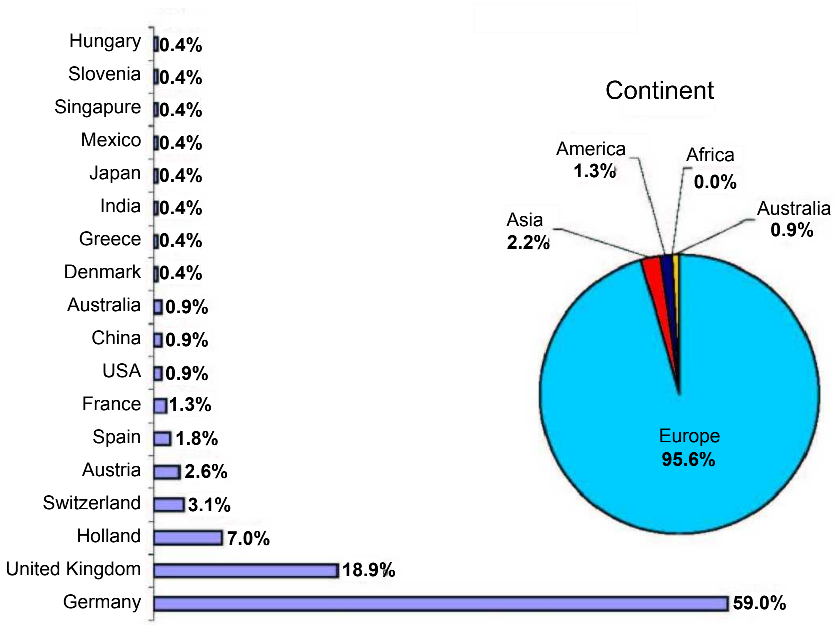


Figure 1.6: Distribution of pneumatic structures with inflatable cushions in terms of continent and country (source: Moritz [15])

The use of inflated cushions is mainly concentrated in Europe, amounting to 95.6% followed by Asia, the Americas, and Oceania. Another interesting piece of information is that 59% of the constructions with inflated cushions are located in Germany.

A material recently used in Europe and for the Olympics in China for pneumatic structures is ETFE. This material exhibits a complex behavior. The yield stress and viscosity parameters show strong dependence on temperature.

Despite the extensive use of this material, few studies have been conducted with focus on constitutive models that take into account its complex behavior.

Several possibilities exit for membrane materials, e.g., reinforced fiber with glass or plastic, a wooden board, a concrete plate, polyvinyl chloride (PVC) coated with polyester, teflon coated with glass fiber, fabrics, kevlar®(para-aramid synthetic fiber), nylon, polytetrafluoretilene (PTFE), and silicon.

The study of nonlinear material behavior has included the material ETFE, which is widely used in pneumatic structures. Poirazis et al. [16] reported that ETFE has gained popularity mainly because of its daylight transmittance and its potential for energy conservation. According to Gómez-González et al. [12], since the development of the ETFE foil, it has been used in most of the studied proposals (84.75%), mainly in the last decade. Self-cleaning, durability, and high light transmission have enabled its the use in many permanent envelopes, thus breaking the traditional relation between inflatable systems and temporary buildings. Other membranes, such as polysulfone (PES) or fiberglass coated with PVC, are also used in large cushions, where high membrane resistance is required. Table 1.1 shows its membrane materials used in pneumatic structures.

Table 1.1: Membrane materials used in pneumatic structures. (source Gómez-González et al. [12])

Material	Percentage	Material	Percentage
ETFE	84.75%	Fiberglass/PVC	1.53%
PES/PVC	4.14%	Fiberglass/Silicon coated	1.74%
PVC	3.70%	Others	4.14%

Pressure–volume coupling is an important factor in the response of pneumatic structures. This coupling is based on the fact that an enclosed pneumatic structure has an internal pressure, and when this structure is subjected to external loads, the volume decreases (increases) and the internal pressure increases (decreases) correspondingly. The concept of deformation-dependent forces also exists in this type of structure. The formulation adopted throughout this study refers to the studies of Hassler and Schweizerhof [17], Rumpel and Schweizerhof [18], Rumpel [19], Bonet et al. [20], and Berry and Yang [21]. Pressure–volume coupling reveals the observable feature that the pressure of an enclosed fluid provides additional stiffness to the inflatable structure, which is analogous to the behavior of a membrane on elastic springs. This coupling is not considered in the conventional programs of the finite element method.

1.3 Formfinding

Formfinding is a process of optimization that results in an optimal form in the equilibrium configuration for a given initial topology with fixed prestress loads and boundary conditions.

The computational methods of formfinding are divided into three groups: simulation of hanging models, numerical simulation of soap films and structural shape optimization.

Hanging models are based on experimental models. These models were improved by Isler [22], and they are used to generate the form of arch–free bending when subjected only to an axial compression load. The objective of hanging models, as defined by Bletzinger [23, 24, 25], is to achieve the transition from a tension structure to a membrane structure by minimizing the bending part of the strain energy. The optimal shape generated by using hanging models is the result of mechanical deformation for one load case. Stability effects cannot be considered in hanging models.

Plateau demonstrated by numerous experiments that every contour of a single closed curve bounds at least one soup film (Lewis [26]). According to Otto [27] soap films can not be subjected to shear. The biaxial stress state of soap films is defined as a spherical tensor, in analogy with the stress state induced by hydrostatic pressure, because the absence of shear stresses generates normal stresses equally in all directions. Dent [4] has reported that a soap bubble is mounted by the surface tension forces acting on both sides of the soap film. Because of the uniformity of these forces, the main characteristic of the film is to form shapes with minimal surface area, in which the walls are stressed equally at every point and in all directions, with no concentration of stress at any one point. Stresses are equalized by liquid flow in the soap film, and therefore, stress peaks cannot occur under any circumstances. Therefore, the analysis of soap films is considered important for the design of membrane structures.

Structural shape optimization has been described by Bletzinger [24] as a more general tool, which the design variables are the coordinates of the model. Botkin [28] reported that structural (sizing) optimization has been considered to be the minimization of structural mass by varying member sizes and plate thicknesses of a model in which the geometry remains unchanged.

Bonet and Mahaney [29] used algorithms of formfinding and observed that in the case of membrane structures it is possible to start with an initial geometry and determine the surface geometry subjected to dead load. In a typical process of formfinding, it is conventional to start with a flat initial geometry. The boundary constraints are set for displacements at points on the boundary mesh. After the boundary constraints are set, steps of formfinding are necessary to obtain a minimal surface. For each step, the reference configuration is defined as the final shape of the previous step.

1.4 Cutting patterns

Generally, membrane structures have curved shapes. To build such curved shapes film strip of a certain width are joined. The smaller the width of the strip, the closer is the obtained curved surface. This building process is analogous to the process of manufacturing clothes. The pieces of fabrics are cut in order to obtain curved forms. The available width size of the membrane fabric also defines the cutting patterns.

Linhard [30] developed an approach called formfinding via cutting patterns that adjusts the stress state already during the formfinding process in an iterative procedure, in such a way that the final form is the equilibrium shape for stresses resulting from assembling the cutting patterns, while keeping the difference between the actual and desired stress state as small as possible. Linhard [30] developed an approach called formfinding via cutting patterns, which employs an iterative process to adjust the stress state during the formfinding process. This adjustment is such that the final form is the equilibrium shape for stresses resulting from assembling the cutting patterns, and the difference between the actual and desired stress states is kept to minimum. Figure 1.7 shows the cutting patterns for a six-point tent; figure 1.8 shows its building process.

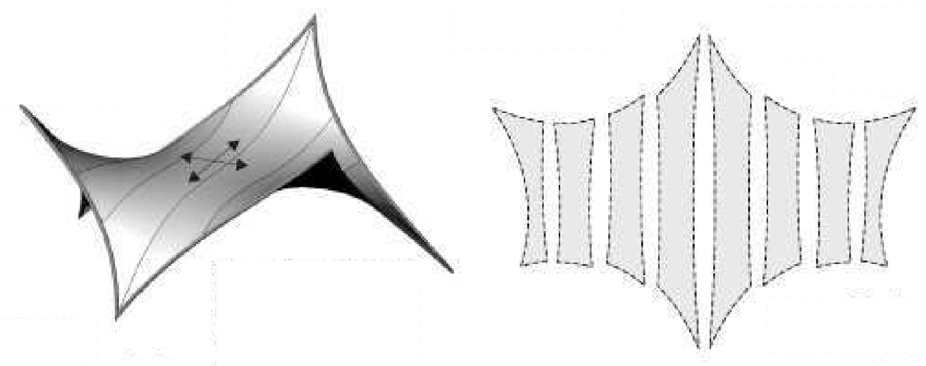


Figure 1.7: Cutting patterns of six-point tent (source: Linhard [31])

The plane strips can be divided using a geodesic line or a cutting line. The difference between geodesic and cutting lines can be seen in figure 1.9. According to Ishii [32], in the cases of simple curved surfaces and curved surfaces with low rise, a cutting pattern can be drawn on a strip without using the geodesic lines. However, in the cases of complex curved surfaces and those with high rise, the use of geodesic lines is more recommended.

For more details of cutting patterns, refer to the studies of Linhard [30], Ishii [32], and Bletzinger et al. [33].

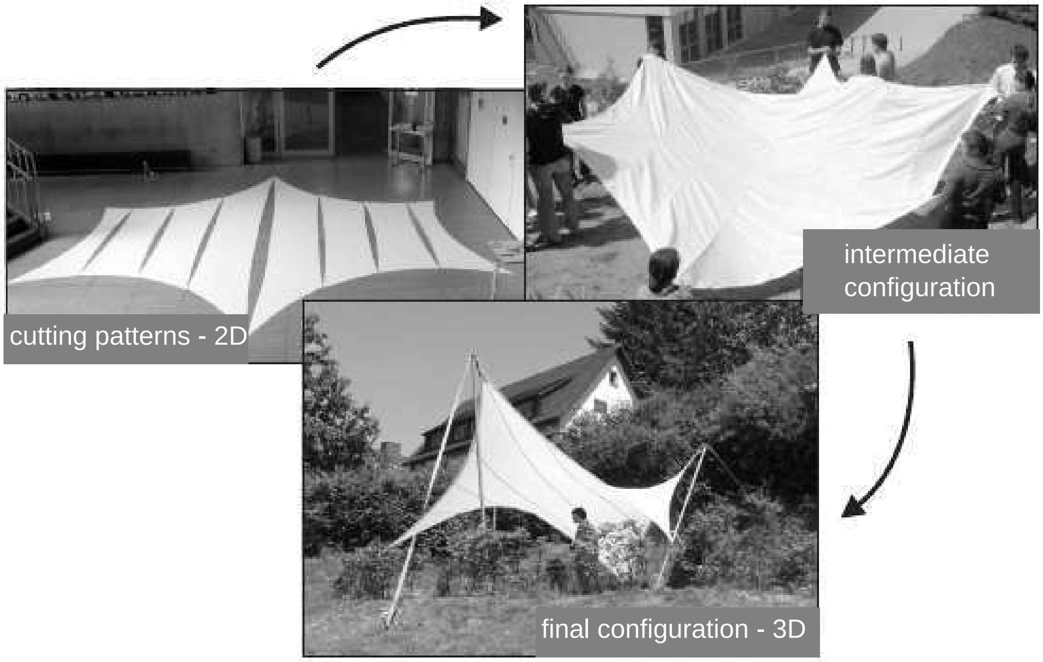


Figure 1.8: Building process of six-point tent (source: Linhard [31])

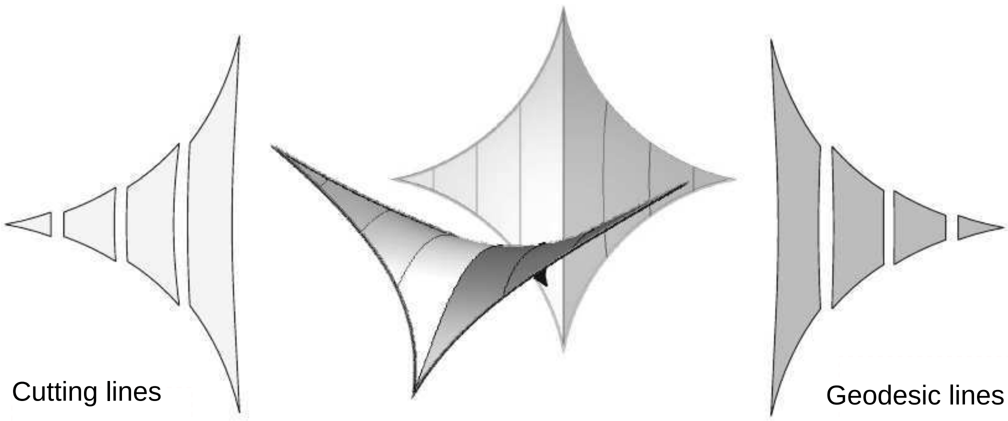


Figure 1.9: Influence of pattern definition on membrane structures (source: Linhard [31])

1.5 Wrinkling in membranes

Wrinkling in membranes is a widely studied topic because of the large number of membrane structures that exhibit wrinkling. The concepts of wrinkling in membranes are briefly described here. The present study does not consider wrinkling in the implementation, because typically, inflated cushions do not exhibit wrinkling.

According to Schoop et al. [34], membranes cannot carry compressive in-plane loads because they do not possess any flexural stiffness. In this case, membranes wrinkle.

Vázquez [35] reported that at any point on its surface, a membrane must be in one of three states. In the slack state, the membrane is not stretched in any direction. In the taut state, the membrane is in tension in all directions. If the membrane is neither taut not slack, it is in the wrinkle state corresponding to uniaxial tension. In the slack or wrinkled state, the real configuration of a membrane is undefined. Figure 1.10 shows the configurations for the three states.

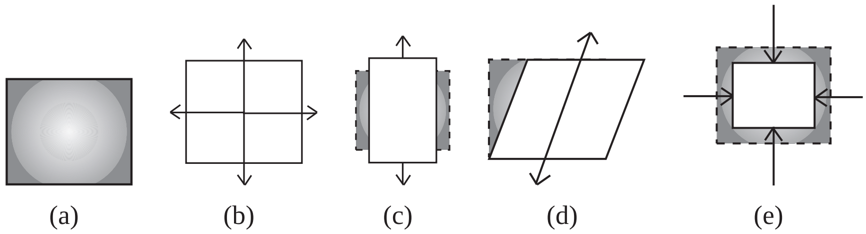


Figure 1.10: Principle states of membranes: (a) reference, (b) taut, (c) and (d) wrinkle, and (e) slack (source: Jarasjarungkiat et al. [36])

Wrinkling experiments on initially flat, thin, linear-elastic isotropic foils subjected to in-plane loads are presented in the work of Wong and Pellegrino [37]; and a wrinkled membrane is shown in figure 1.11.

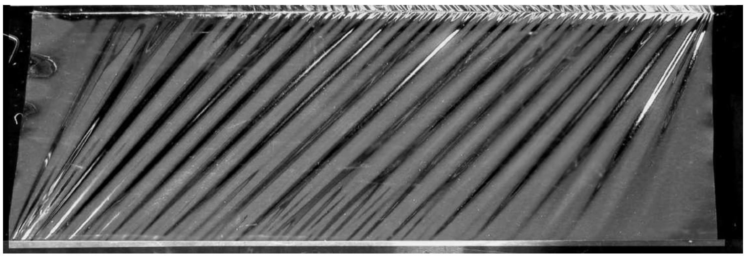


Figure 1.11: Wrinkled membrane (source: Wong and Pellegrino [37])

1.6 Objective

This study focuses on two main objectives:

– research on material models suitable for membrane materials.

– analysis of the influence of the pressure–volume coupling in inflated cushions.

1.7 Thesis outline

The characteristics and types of pneumatic structures are presented in chapter 2, which also presents the membrane formulation used in the numerical analysis by the finite element method.

Chapter 3 presents the material models for membranes. Because of the large variety of membrane materials available for membrane structures, different material models are presented and implemented. These material models are elastoplastic and elastoviscoplastic for small strains, and hyperelastic, elastoplastic, and elastoviscoplastic for large strains.

A new material model based on non uniform rational basis splines (NURBS) surfaces is proposed and is presented in chapter 4. NURBS is a mathematical representation of a 3D geometrical shape and is used for obtaining curves and surfaces. In this material model, the NURBS surfaces are used to represent the constitutive relation between stresses and strains. The definition and formulation of NURBS curves and surfaces and examples of validation for the proposed material model are also presented in chapter 4.

Chapter 5 presents the discussion on pressure–volume coupling, which is applied to pneumatic structures. The main objective of this coupling is to take into account the influences of volume variation, which leads to the change in internal pressure. The formulation for the numerical analysis in the finite element method is presented in conjunction with the analytical analysis that enables the validation of the numerical implementation.

The implementation of pressure–volume coupling and the material models for inflatable structures was carried out in the structural analysis program developed by the research group at TUM. This program is called CARAT++ (Computer Aided Research Analysis Tool) and was initiated by Kai-Uwe Bletzinger, Hans Stegmüller, and Stefan Kimmich at the Institut für Baustatik of the University of Stuttgart in 1987.

Examples of application of material models for membranes and pressure–volume coupling are presented in chapter 6, which also discusses an example of a real pneumatic structure.

Finally, the conclusions on the material models for membranes, conclusions of the analysis considering pressure–volume coupling, and suggestions for future studies are presented in chapter 7.