Tensile Membrane Structures

"Form, Material and Design"

Master Thesis
Anhalt University of Applied Sciences
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Master-Thesis

“Tensile Membrane Structures - Form, Material and Design”

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Statement

I hereby declare that the work presented in this Master Thesis, entitled

“Tensile Membrane Structures - Form, Material and Design”

is entirely my own and that I did not use any sources or auxiliary means other than those referenced.

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“Honey remained, clay not” *

The two basic needs in the human-nature relationship are food and shelter. The Turkish folk statement above is expressing a preference made between these two basic needs, by using the honey and clay opposition. Considering the period and geography in which this statement came up, honey is one of the most valuable food items. Clay is the most abundant material in nature obtained by mixing soil and water. The usage of clay as a building material has a history of thousands of years. The human have been using this material since the beginning of the settled life. In this statement, the vital importance of the building need of the human species is expressing in a striking language, by the claim that “clay is more valuable than honey”. In this context, the statement is expressing a universal truth in the human-nature relationship. The following sentence may be extracted from this statement.
“We need more structure (to produce the food which necessary to live).”

The human of this age is facing new realities in his relationship with nature. Considering the growing world population, natural resources are rapidly exhausting. For the continuation of the current human presence, the developing new building techniques which led to making more strong structures using less material is a necessity. This necessity has an economical, ecological and ethical basis. Lightweight structures are the result of this kind of material and construction quest.

* ***“Bal artmış, balçık artmamış”*** *Unutulmuş, fakat güncel bir Türk halk deyimi*

Preface

The first scientific paper which states the necessity of designing lightweight structures was written by German engineer Fritz Leonhardt (1909-1999), in 1940. In this article, Leonhardt defines designing lightweight structures as a necessity, due to the problem of material supply at that period.[AL], [DR] It is aimed that a structure made within the responsibility should be as light as possible. Lightness can be achieved by reducing the total amount of material used in its manufacturing process of a structure. The primary task of a structure is to resist external loads. The smaller ratio between the weight of the structure and the load-bearing capacity of the structure indicates the degree of lightness of that structure. A suspension bridge built using steel cable is lighter than a bridge made with truss.[SC]

The basic question for lightweight structures is ”how can a structure be designed using less material? The adequacy of the answer to this question depends on the progress of material science and structural design knowledge. Membrane structures provide lightweight structure solutions. These structures have a wide form and construction options. Tensile membrane structures, cable-net structures, pneumatic structures, lattice grid shells, geodesic domes are an example of lightweight structures. Each of these structures is an answer to the question mentioned above. All of these building techniques emerged as a structural design alternative after the 1950s. This is because appropriate materials and design methods were developed in this period.

Historical Background

The needle was invented in 60.000 BC. Thanks to this invent, it became possible to combine animal skins. Symbolically, the date of this invention can be regarded as the beginning of membrane structure manufacturing.[DR] The Ice Age human, made shelter and clothing using animal skin to protect himself from nature. These people lived not only in caves but also in tents they made using animal bone and skin. When the Ice Age ended, the settled life began due to agriculture revolution. They built houses using mud bricks from clay.[LB] But, nomadic people continued to live in tents. Today, the "yurt" and "black tent" with an ancient background is still using by nomads.

Nomads have developed portable, easy to transport, lightweight tent types due to their necessities. They used fabrics made of goat hair and animal skin as cover at this tent. The "tepee" used by North American Indians, the "yurt" and the "black tent" seen in Asia are examples to those. In Egyptian, Roman and Asian civilizations, the tents made of animal skin and woven fabrics were used for military purposes. In Rome, the amphitheater's spectator areas were shaded by the linen fabrics attached to the ropes. From Rome to the 18th century, little progress was made in the tent forms. This is because the existing materials cannot transfer enough force and there are no suitable bonding techniques.[FR]

With the industrial revolution, the producing of linen, cotton and wool yarns were started by using machinery. In this period, progress was made in wire rope manufacturing. The first suspension bridge using wire rope instead of wrought iron chain or bar was designed in France, in 1829. After the 1800s, circuses have become popular entertainment tools. As the railroads became widespread, traveling circuses emerged in America. Mobile circus companies needed lightweight an easy portable tents. The circus tent industry developed for this need. The circus tent producing company Stromeyer was founded in Germany, in 1872.[FR] The first examples of tensile membrane structures, in the modern sense, were produced in this company, in the 1950s.

One of the important results of the industrial revolution is the development of new materials. Due to technical developments in steel production, from 1864, steel sections at different grades became affordable and widely available.[BK] The modern wire rope was developed by German mining engineer Wilhelm Albert to be used in the field of mining in 1831-1834.[WW] The production of the first polyester fiber was announced in 1941 by the British chemists John Rex Whinfield and James Tennant Dickson.[WY] The production of these materials provided the basis for the development of lightweight constructions.

Pioneers

Russian engineer Vladimir Grigorevic Shukhov (1853-1939) is one of the most important pioneers of steel lightweight construction systems. Shukhov designed hyperboloid towers, roofs and tent structures made of steel lattice grid shell systems. The world's first anticlastic form of steel tensile structures was designed by Shukhov. Shukhov impressed many architects and engineers who came after him. Today, these effects continue to increase.[KD], [BK] The most important invention of Shukhov is steel lattice grid structures. Shukhov developed these systems after an intensive research process to create a light, economical, strong construction system. Shukhov discovered that if the lengths of the elements forming a structure are equal, the loads would be evenly distributed on the building surface, so that lightness and strength could be achieved together. In 1895, he patented this discovery. With this construction technique, he built wide-span tent structures for the 1896 Russia Nizhny Novgorad Fair. The grid roof of these tent structures consisted of thin steel strips which were crossed and riveted together.[ED] The steel grid, which forms the roof of the structure, gained a tension due to its own weight and was able to resist external loads due to this pretension.[DG] Shukhov, constructed hyperboloid towers and double curvature shell vault roofs using the same construction technique. The elements forming the surface was under the compression load at these structures. Many of these structures are standing today. Until the Polish-American architect Nowicki designed the Dorton Arena, the grid roof construction technique built with elements under tension had been forgotten.[BK]

Yurt tents have been using by the nomads in Central Asia for thousands of years. These tents are the richest systems in terms of structural design within the traditional portable tent systems. It consists of many complicated details and structural elements. The walls of the yurt tents are surrounded by a shell from the timber grids. This grid shell provides a high degree of stability and strength to the yurt tent. Shukhov's grid shells which built with compression elements are similar in terms of form and function with the yurt tent's grid shell wall. Shukhov, might have been inspired by the yurt tent grid wall. The yurt grid shell walls have one directional curvature and most of the grid shell structures designed by Shukhov have two directional curvature (synclastic and anticlastic).

Roughly fifty years after Shukhov's lattice grid shell works, a roof covering technique with anticlastic surface was applied by architect Matthew Nowicki (1910-1950) and engineer Fred Severud (1899-1990) at the Dorton Arena project in America, in 1952. In this project, the roof covering system consists of a cable-net arranged in two opposite directions. The loads in the cable-net are transferred to the arch-shaped frame which the cable-net is connected. The roof surface gains its anticlastic form due to the geometry of arch frame. The Dorton Arena roofing technique created new design ideas.[DG] The Dorton Arena project is the first important application designed with the prestressed cable-net roofing technique. In 1951, while the project was under construction, German architect Frei Otto (1925-2015) as a student met Severud who the engineer of the project, in America.[ST] After examining this project, Otto became interested in suspended roof techniques.[MD] Otto set out from this project while preparing his dissertation. Nowicki and Severud's cable-net roof inspired Frei Otto's work and led a very fruitful collaboration with tent maker Peter Stromeyer.[DG], [BN]

The basic design idea of American thinker, inventor Richard Buckminster Fuller (1895-1983) is based on the idea that it is possible to do more with less. According to Fuller, the basic problem of humanity is food and shelter. These problems can be solved by an economic and effective design approach.[WN] One of the Fuller's main interest areas was to use technology for improving housing by restructuring housing design and production techniques.[BF] According to Fuller, a structure should be evaluated not only in terms of aesthetics but also in terms of its lightness or ecological harmony.[MG] Fuller made many inventions and received patents. Fuller designed a self-contained structure (Dymaxion House) and invented the low fuel consumption aerodynamic car (Dymaxion Car). Geodesic spheres can be shown as the most famous discovery of Fuller.

A geodesic sphere is an ideal construction technique for covering an area with high strength using less material.[KD] Fuller worked for many years to develop a spherical surface typology consisting of elements which have an equal length as possible. Fuller achieved to do this converting the sphere to the 20 equal triangles (icosahedron) surface. For a more refined spherical surface, each triangle was divided into sub-triangles.[KP] But, the geodesic sphere had been discovered before Fuller by German engineer Walter Bauersfeld (1879-1959). Bauersfeld applied his design at the Zeiss Planetarium roof, in 1922. Fuller, unaware of this design, rediscovered the geodesic sphere with his calculations. Fuller constructed his first geodesic dome using aluminium profiles and vinyl covers, in 1949. His first commercial client was the Ford Motor in 1953. The Ford administrative building courtyard in Michigan had to be closed with a dome, and the engineers designed a roof structure weight of 160 tons. The project could not be implemented because the existing building could not carry this weight. The problem solved by Fuller, he designed a geodesic dome to cover the courtyard, which reduced the roof construction weight to 8.5 tonnes in total.[WN] The USA joined in Expo 67 with a geodesic sphere designed by Fuller. One of the important applications of geodesic sphere is the Eden Project constructed in England, in 2000.

Method

The degree of lightness of a structure is understood by the ratio between weight of the structure and the load-bearing capacity of the structure. In this context, lightness is a measurable criterion. A structure is primarily resisting to environmental loads. These loads are snow, wind and earthquakes. The capacity of a structure to resist these loads depends on the form of the structure. The searching the most appropriate form to increase the load carrying capacity of the structure is called "form- finding". While searching the ideal form for a structure, natural phenomenas are a guide. The gravity load and minimum energy principle are the practical form builder effects seen with the naked eye. In this context, the "form-finding" is an experimental process and takes its origin from natural phenomena. The fact that living or non-living element built a form by itself under the influence of natural phenomena is called "self-forming" process.

Spanish architect Antoni Gaudi's Colonia Güell Church is an example of a design based on the laws of nature.[TM] Architect Antoni Gaudi (1852-1926) used the curves of the catenary in his works. Gaudi used these curves for the first time in the design of the Colonia Güell Church. An inverted catenary curve is an ideal form only for an arch carrying its own weight. This arch form shows axial compression under its own weight, and there is no significant bending moment in the arch construction.[LR] Antoni Gaudi is perhaps the first person to use a physical model's self-forming process to determine the entire geometry of a structure. Gaudi defined the form of the Colonia Güell Church using a three-dimensional physical model. For this target, he formed a funicular system suspended on a platform scaled 1:10. Gaudi simulated dead load by hanging bullet-filled bags to the system consisting of ropes. This physical model has created a equilibrium figure that determines a structure resistant to its own weight. When Gaudi reversed the equilibrium figure which he had got from the physical model, he obtained a structural form in which the elements forming the system carried only axial compression load under its own weight without exposure to the significant bending moment.[WD]

Swiss engineer Heinz Isler (1926-2009) is one of the pioneers of reinforced concrete shell structures. Isler is famous with his form-finding techniques based on the experimental method. In Isler's designs, his close relationship with nature was effective. He was inspired by mussels, nuts, and eggshells. Isler's shell structures formed experimental methods are the result of such forms shaped by nature. Isler, through this approach, achieved to produce the strong solid structural forms using the least amount of material.[KT] Isler developed different methods to find the form of his reinforced concrete shells. The most satisfactory forms were obtained from using hanging cloth pieces. His iconic project the Deitingen Service Station was designed using this form-finding method. When Isler hanged a wetted piece of cloth from four points at the freezing night cold, the shape of the cloth under gravity became frozen and turned into a shell by the time. Isler developed his most efficient form-finding method based on this experiment. He hung a piece of cloth plastered with a special mixture containing gypsum on the scaled platform he prepared. When the shape formed under the effect of gravity solidified, he obtained a stable scaled model for the real shell structure. Isler numerically defined the geometry of his scaled model on a coordinated platform, with sufficient precision for production using manual tools.[CH]

Previously, In order to show the relationship between nature and design, the terms"bionics“ and "biomimicry" were used. Currently, the term ”biomimetic“ is used instead of these terms. Biomimetic requires an understanding of biological structures and processes, their similar technological applications, methods or procedures. Biomimetic needs to an understanding of the principles of nature, not of mimicry of nature in a material, functional or creative context. Engineers and architects, such as Richard Buckminster Fuller and Frei Otto, have been interested in natural structures, after the 1950s, they have developed structures that not lost their actuality. Frei Otto tried to understand the functional basis of natural forms and building processes in collaboration with other experts.[PH]

Frei Otto, the pioneer of tensile membrane structures, was met with Johann-Gerhard Helmcke who is anthropology and biology professor (1908-1993), in 1961. Otto's main interest was limited with structural lightness research until this met. In this period Otto was working on minimal forms of soap films. After meeting Helmcke, Otto's scope of the form studies expanded. In particular, his examination of diatom and radiolaria photographs added biology to the Otto's field of study. Otto saw the minimal forms of soap films, in these diatom and radiolaria photographs. Otto and Helmcke tried to understand these forms and the reason of similarity behind these forms in their work that lasted decades. The collaboration between Helmcke and Otto continued until 1993.[FB] Researches on about natural forms and the processes in living and non-living objects in nature, started a design approach valid today and tomorrow. Identifying the similarities of forms in nature and studying the background of these similarities can be considered as a valid design approach for all times. Frei Otto and his team developed a design idea that not only helps us as a design theory but also enables us to fulfill our responsibilities for the future.[AL]

Progress

Reformist architects and engineers who want to break tradition after the World War II,[KN] new materials developed during the war, experience gained by the building industry, developments in computer science and structure analysis techniques, new theoretical knowledge about the dynamic effects of the wind gained by the collapse of the Tacoma Narrows Bridge (1940),[FR] led to a historical progress in the lightweight construction area. During the studies conducted by Frei Otto, at the Stuttgart Technical University, Lightweight Structures Institute (IL), comprehensive theoretical and practical information was produced on the design and production of tensile membrane structures.

Otto has designed examples of membrane structure systems such as cable-nets, grid shells, pneumatic structures, and foldable structures. These designs were realized with the contribution of many experts from different fields. In terms of the history of lightweight structures, the **Expo 67 German Pavilion** (1967 - with Architect Gutbord), **Munich Olympic Stadium** (1972 - with Architect Behnisch), **Mannheim Multihalle** (1975 - with Architect Carlfried Mutschler and Joachim Langner) are groundbreaking project examples.

Frei Otto was born in Germany, in 1925. Otto received the right to enroll to the faculty of architecture in 1943, but he was taken to the army in the same year. In 1945 he was arrested as a prisoner of war. He stayed in the camp where there were war prisoners in France, along the two years. He took part in the architectural team at this camp. Otto developed the concept of "covering an area using the least amount of material" here. He was released in 1947 and returned to the home. He graduated from the Faculty of Architecture of the Technical University of Berlin in 1952. In 1950-51, he went to America with a scholarship and explored the works of important architects. He also studied sociology and urban development at the University of Virginia at this period. In 1952, he founded his own architecture office in Berlin. He completed his Ph.D. thesis, titled the Suspended Roof (Das Hangende Dach, Gestalt und Struktur) at the Technical University of Berlin, Department of Civil Engineering, in 1954. The same year, he started to work with the tent maker Peter Stromeyer.[MK], [DC], [MG]

He applied the first examples of the modern tensile membrane structures for Federal Garden Exhibition, in 1955 (Cologne) and in 1957 (Kassel). Although these systems had a simple and modest appearance they reflected technical excellence.[NR] These first studies provided Otto to be recognized nationally.[MK] In each of these studies, Otto tried new form ideas, different membrane materials, different pretensioning techniques, and assembly methods.[FR], [DG] These studies together with Peter Stromeyer are the first examples of modern tensile membrane structures with anticlastic surfaces. He founded the “Institute for the Development of Lightweight Structures” in Berlin, in 1958. In the following years, he lectured as a guest professor at major universities of America. In 1961, he founded the research group "Biology and Structure" in Berlin with anthropologist and biologist J. G. Helmcke.[MK]

Fritz Leonhardt (1909-1999) invited Otto to establish the Lightweight Structure Institute (IL) to the University of Stuttgart.[AL] The Institute was founded in 1964. Within the scope of the Institute's studies, two special research projects, namely SFB 64 (Long-Spanning Surface Structures 1970-1985) and SFB 230 (Natural Structures 1984-1995), were conducted. In the SFB 64 program, studies were carried out on nature and technology, biology and construction.[PH] SFB 64 brought together all the technology, design method and material science required to successfully design and build the Olympic Stadium in Munich.[BN] In the SFB 230 program, architecture, urbanism and the structure of buildings were studied. In this program, ”form-finding“ and “self-forming" processes were taken into account in all living and non-living areas. In this research program, understanding nature was more important than using nature.[PH] In the SFB 230 research project, philosophers, biologists, architects, engineers with different expertise and city planners studied.[AL] The studies in the institute were based on the experimental method. Spider webs, soap films, bamboos, micro-organisms etc. were examined within the "form" concept. Otto and his colleagues interpreted the lightweight tensile structure technique, which has a history of thousands of years, with a new approach based on nature. Most of the tensile membrane structure design and analysis concepts, production techniques that using today are based on the studies conducted at the Lightweight Structures Institute at that time.[BN] This studies, which lasted for decades, led many experts to come up in the field of lightweight structures. Many architects and engineers were influenced by the research of the SFB 64 and SFB 230 about natural structures. These studies led to the understanding of lightweight structures and minimal forms. Considering today's energy and material-efficient building targets, form-finding researches in nature is becoming increasingly important.[PH]

Otto's Expo 67 project, after Shukhov's Nizhny Novgorod and Nowicki's Dorton Arena projects, started a new era in lightweight structure systems area consisting of cable-nets. This project was the first design that revealed Otto's vision.[NR] Otto managed to turn a minimal form he found with soap film experiment into an 8.000m² real project. This structure provided an understanding of the high possibilities of tensile membrane structures due to its form and material. Expo 67 project was structurally made without a mathematical proof. The reason for this is that there is no digital or numerical tool for modeling surface and understanding surface structural behavior. A prototype of a part of the project was made, and loads on the masts were checked using hydraulic jacks on this structure. The Expo 67 project, due to this feature, is an exception in Otto's projects.[MD] Otto has gained international recognition with the Expo 67 project.[MK] This project was realized with the technical contributions of Fritz Leonhardt (1909-1999), Wolfhardt Andrä (1914-1996) and Klaus Linkwitz (1927-2017). This project consists of a polyester membrane suspended from the bottom of a cable-net structure. The Expo 67 German Pavilion project provided a theoretical and practical background to the Munich Olympic Park project.

The Munich Olympic Park is another project consisting of a minimal surface that Otto finds its form with soap films. This project is one of the most important symbols of lightweight structures. The project shows the transition from modeling and analysis methods based on the physical modeling to the numerical modeling and analysis methods using computer technology.[DG], [LW] Due to this feature, the Munich Olympic Park project launched a new era in the methods of design, manufacturing, and analysis of tensile structure systems. The Force Density Method which first numerical form-finding method, was developed by Linkwitz and H. J. Schek in 1969 during the design phase of this project. The project covering an area of 75.000 m², consists of acrylic glass on the cable-net roof structure. The structural calculations of the project were done by Leonhardt and Andrä.

Another breakthrough design by Otto is the Mannheim Multihalle project. Otto created the surface form of this project by inverting the form of a chain mesh under the effect of gravity. The construction of the project consists of timber grid shell which covered with polyester based membrane. The project, covering an area of 7.400m².[WD] Although nearly fifty years have passed, this structure has still a contemporary form. The structural calculations of this project were done by Ove Arup (1895-1988) and Edmund Happold (1930-1996).

Considering the historical significance of the Expo 67 and Munich Olympic Park projects, Leonhardt's contribution to the lightweight structures is important. Leonhardt is one of the most important pioneers of modern civil engineering.[DR] Otto and Leonhardt are the founders of the first special research group SFB 64. This research group prepared the scientific basis for the 1972 Olympic Park project to be applicable. The planning and construction of the 1972 Olympic Park project is proof of Leonhardt's versatility and high engineering capacity. Leonhardt has developed new systems for improved long-span suspension bridges that are more economical than traditional bridge designs. He also pioneered new systems and construction methods for prestressed concrete.[TR]

The importance of Otto is not limited to the fact that he made the first applications of tensile membrane structures.
Otto has tried to develop a philosophical foundation for lightweight structures. According to Otto, these studies on natural structures are part of the process of finding a rational form following natural laws but are also part of a larger vision for a peaceful and free society that is compatible with itself and with nature.[NR] Otto's architecture will always be a reaction to the heavy solid structures that built in the Nazi period for eternity in Germany. Otto's work was, on the contrary, light, open to nature, democratic, low-cost, and sometimes transient.[MK]

Abstract

Tensile membrane structures provide lightweight structure solutions and large spans can be covered quickly and economically using these systems. It offers rich, functional structural solutions with wide form and construction options. In some cases, structures that are not possible to realize by conventional construction techniques can only be constructed with the tensile membrane structure techniques. In this context, these systems have a content that broadens the concept of the structure. Lightness, flexibility, transparency, portability are characteristic features of this structures. Tensile membrane structures are constructed with elements that resist to the tensile load. However, a structure does not consist entirely of elements that only tensile resistant. The tensile loads on the membrane surface are transferred to the compression and bending resistant elements such as mast, beams, arch. Membrane structures differ from traditional building systems in terms of form and structural behavior. These systems show large deformation under external load. In order to eliminate the destructive effects of this deformation, there are specific principles that must be followed in the design phase. The aim of this thesis is to explain the basic design and analysis concepts of tensile membrane structures. The thesis consists of four parts. The first and second parts are independent of each other. The third and fourth parts are connected to each other.

Membranes as a material have roughly 1mm thickness and 1kg/m^2 weight. The using of such an elegant material as a structural element which will resists snow and wind loads can only be achieved in a special structural form. For tensile membrane structures, form means more than a shape or geometry. The load bearing character and capacity of the membranes depend on the form of the membrane surface. In the first part, the concepts and principles of forms were tried to be explained with concrete examples as much as possible. A sample analysis was performed to show the basis of the physical equilibrium state of the form, it is in the Appendix 1.

The materials used in the tensile membrane structures are generally polymers based products. Membrane materials are developed to provide the highest resistance to structural and environmental impacts, starting from molecular level. Although these materials are light and thin, they perform a heavy duty under environmental influences. Membranes usually consist of many layers. Each layer plays an important role in the fulfillment of these heavy duty tasks. Structural membranes exhibit nonlinear complex behavior under the load. A tensile membrane structure system is designed by considering these behaviors. In the second part of the thesis the materials used in the tensile membrane structures and its basic properties were explained.

In the third part of the thesis, a tensile membrane structure system with a cantilever construction was prepared as a design example. The reason for choosing a cantilever system as an example is that these systems exhibit relatively more complex structural behavior under load. Therefore, the design of these systems requires special care. The detail drawings of important connection point of the design were prepared. Possible alternatives for the steel construction were evaluated. The designed system is not intended for a particular purpose. The design is just an example to explain basic architectural design concept.

In the fourth part, structural analysis of the designed system was performed. The basic purpose of the analysis is to explain the sequence of the analysis process. The educational version of the ixCube nonlinear analysis software was used for analysis. Snow and wind loads were applied to the membrane surface in accordance with Eurocode. The Istanbul conditions were taken into consideration for the external loads. The ixCube has a plug-in that checks the steel construction according to Eurocode. The reactions at the steel construction were checked by manual calculations. The purpose of manual calculations is to achieve the same results with software. The analysis does not cover all the structural calculations of the structure.

Özet

Asma germe membran yapı sistemleri "hafif yapı" çözümleri sağlar, bu yapı tekniğiyle geniş açıklıklar hızlı, ekonomik bir şekilde kapatılabilir. Bu sistemler zengin form ve konstrüksiyon seçeneğine sahiptir. Bazı durumlarda, geleneksel yapı teknikleriyle inşası mümkün olmayan yapılar ancak membran yapı teknikleriyle inşa edilebilir. Bu bağlamda bu sistemler "yapı" kavramını genişleten bir içeriğe sahiptir. Hafiflik, esneklik, şeffaflık, taşınabilirlik membran yapı sistemlerinin karakteristik özellikleridir. Membran yapı sistemleri çekmeye çalışan elemanlarla inşa edilir. Ancak bir yapı tamamen çekmeye çalışan elemanlardan oluşmaz. Membran yüzeyde oluşan yükler basınca, eğilmeye çalışan dikme, kiriş, kemer gibi taşıyıcı elemanlara aktarılır. Membran yapı sistemleri geleneksel yapı sistemlerinden form, malzeme ve yapısal davranış olarak farklıdır. Bu sistemler yük altında büyük deformasyon gösterir. Bu deformasyonun yıkıcı etkilerini gidermek için tasarım aşamasında uyulması gereken, bu sistemlere özgü prensipler vardır. Bu tezin amacı, asma germe membran yapı sistemlerinin temel malzeme, tasarım ve analiz kavramlarını mümkün olduğunca somut örneklerle açıklamaya çalışmaktır. Tez dört bölümden oluşmaktadır.

Bir malzeme olarak membran, kabaca 1mm kalınlığında ve 1kg/m^2 ağırlığındadır. Böylesine zarif bir malzemenin, kar ve rüzgar yüklerine direnç gösteren bir yapı malzemesi olarak kullanılabilmesi ancak yapısal bir formla sağlanabilir. Membran yapı sistemleri için "form" bir yüzey geometrisinden daha fazla anlam taşır. Asma germe membran yapı sisteminin yük taşıma karakteri ve kapasitesi membran yüzeyin formuna bağlıdır. Birinci bölümde bu sistemlerin "form" kavramları ve prensipleri mümkün olduğunca somutlaştırılarak açıklanmaya çalışıldı. Formun sahip olduğu fiziksel denge durumunun matematik temellerini göstermek amacıyla bir örnek çözümleme yapıldı. Bu çözümleme örneği Appendix 1'dedir.

Asma germe membran yapı sistemlerinde kullanılan malzemeler genellikle polimerler tabanlı ürünlerdir. Membranlar moleküler düzeyden başlayarak yapısal, çevresel etkilere karşı en yüksek direnci sağlayacak şekilde geliştirilir. Bu malzemeler hafif ve ince olmalarına rağmen çevresel etkiler altında ağır bir görev yerine getirir. Membranlar genelde bir çok katmandan oluşur. Membranın bu ağır görevleri yerine getirmesinde her katman önemli bir işlev görür. Yapısal membranlar yük altında doğrusal olmayan karmaşık davranış gösterir. Bir membran yapı sistemi bu davranışlar dikkate alınarak tasarlanır. İkinci bölümde membran yapı sistemlerinde kullanılan malzemeler ve bu malzemelerin temel özellikleri açıklanmaya çalışıldı.

Üçüncü bölümde, konsol taşıyıcılı bir membran yapı sistemi, tasarım örneği olarak hazırlandı. Bir örnek olarak konsol sistem seçilmesinin nedeni, bu sistemlerin yük altında göreli olarak daha karmaşık yapışal davranış sergilemesidir. Bu nedenle, bu sistemlerin tasarımı özel bir itina gerektirir. Hazırlanan tasarımın önemli bağlantı noktalarının detay çizimleri hazırlandı. Çelik konstrüksiyonun etkili bir yapısal geometriye sahip olması için, olası alternatifler değerlendirildi. Tasarlanan sistem belirli bir amaca yönelik değildir, membran yapıların tasarım sürecini açıklamak için hazırlamış bir örnektir.

Dördüncü bölümde, tasarlanan sistemin yapısal analizi yapıldı. Bu bölümün amacı analiz sürecini açıklamaktır. Analiz için ixCube nonlinear analiz yazılımının eğitim versiyonu kullanıldı. Membran yüzeye, Eurocode'a uygun olarak kar ve rüzgar yükleri uygulandı. Uygulanan yükler belirlenirken İstanbul koşulları dikkate alındı. ixCube yazılımı, çelik konstrüksiyonun Eurocode'a göre kontrolünü yapan bir eklentiye sahiptir. Çelik konstrüksiyonda oluşan gerilmeler elle yapılan hesaplarla kontrol edildi. Elle yapılan hesaplamaların amacı, bu yazılımla aynı sonuçlara ulaşmaktır. Ayrıca, bağlantı noktalarının kaynak yeterliliği elle yapılan hesaplarla kontrol edildi. Yapılan analiz, sistemin tüm yapısal hesaplarını kapsamamaktadır.

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Appendix

Part I
Form

Frei Otto built his first membrane structure project in 1955, its measure was 12.5x12.5m. That simple roof over the music pavilion has started a new era in the field of membrane structure. This project is the first presentation of the prestressed membrane structure principle which is double curvature.[KN]

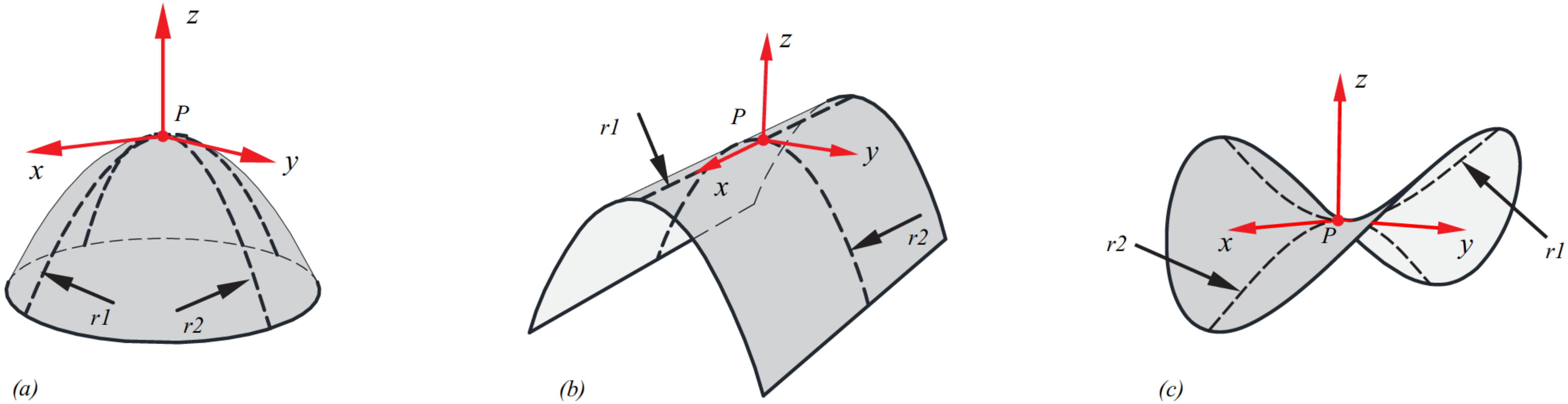
Under Frei Otto management, between 1964 and 1991, at the Institute for Lightweight Structures (IL) University of Stuttgart, the structural forms suitable for lightweight construction principles were explored. The "lightweight construction technique" means is that optimize the shape of the structure by using the least amount of material to provide the highest stability and strength.[LW]

The smaller ratio between the weight of a structure and its load-bearing capacity indicates the degree of lightness of that structure.[SC] The stability is the resistance of a structure which exposed to the external loads, to the displacement. The main loads for a membrane structure are snow and wind loads. Tensile membrane structures are constructed using structural elements which carry the loads only as a tension. Structural membranes and steel cables are such kinds of materials. It is assumed that there are no structural properties other than the tension capacities of these materials. A membrane structure surface bears all the loads as a tension. The load bearing capacity of a membrane surface depends on its form and amount of prestress it has. In this context, the meaning of "form" is not shape. The form refers to a structurally load bearing surface system. All elements in that system are in tensile load only, to form a physically stable surface.

When we look at a membrane structure surface, all of the elements we saw are part of the physical equilibrium state. In this context, membrane structures don't contain decorative or non-functional elements. Membrane surface and edge curvatures are the components of the physical equilibrium state.

1. Basic mathematical concepts

1.1 Gaussian curvature



Synclastic surface

P Eliptic point

r1 Negative curvature

r2 Negative curvature

$$K = \frac{1}{r_1} \cdot \frac{1}{r_2} > 0$$

Flat surface

P Parabolic point

r1 (∞)

r2 Negative curvature

$$K = \frac{1}{r_2} \cdot 0 = 0$$

Anticlastic surface

P Hyperbolic point

r1 Positive curvature

r2 Negative curvature

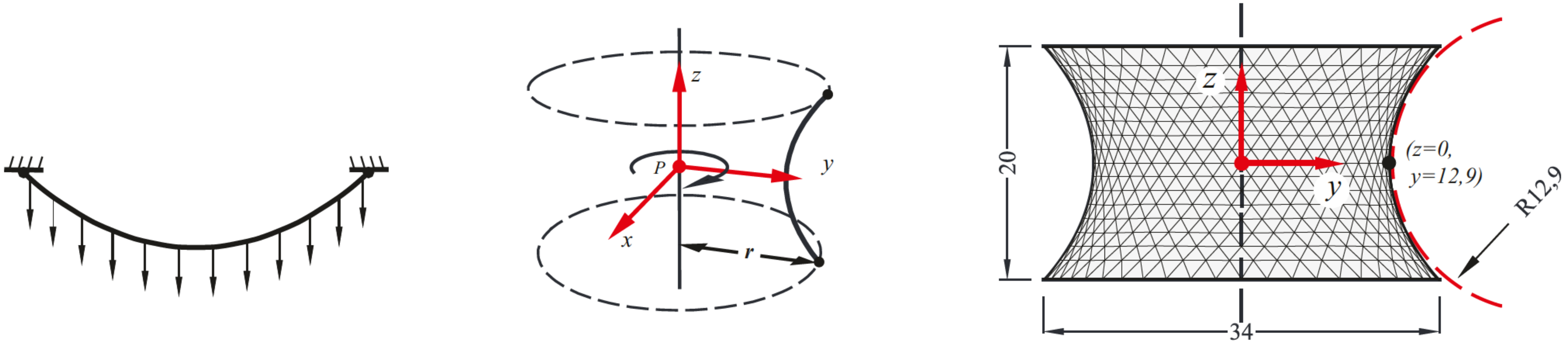
$$K = \frac{1}{r_1} \cdot \frac{1}{r_2} < 0$$

Figure 1.1 Gaussian surface definition

K: *Gaussian curvature,* ***P***: *Reference point,* ***r***: *Curvature radius,* ***xy***: *Tangent plane,* ***zy***, ***zx***: *Principal curvature section planes,* ***z***: *Normal vector direction*

Surfaces are mathematically defined by the Gaussian curvature values. Figure 1.1 shows three basic surface types.
At the **P** point of the surface, the axis perpendicular to the tangent plane is the normal of this surface point. In the surface examples in figure 1.1, the XY plane is the tangent plane for point **P**. The z-axis drawn perpendicularly to the XY plane is the surface normal. The lowest and highest curvatures that occur when the tangential plane is cut by two axes of 90 degrees to each other are principal curvatures for the **P** point. The principal curvatures are indicated with **k1** and **k2** values. The **k =1/r** equation indicates the curvature value for the section at **P** point. The multiplication of **k1** and **k2** for two principal axes expresses the Gaussian curvature value. The surface geometry is defined depending on the result of the equation whether it is smaller or greater than zero. If the K value, greater than zero the surface is synclastic. If it equal to zero the surface is flat. If it smaller than zero the surface is anticlastic. The inner surface of a torus is anticlastic, and the outer surface is synclastic.

1.2 Catenary curve and catenoid surface



(a) Hanged chain (Catenary curve) *(b) Rotating the catenary curve* *(c) Catenoid surface*

Figure 1.2 Catenary curve and catenoid surface

When a flexible material suspended from the both ends forms a curve due to its own weight. (Figure 1.2.a) That curve is called catenary curve. The flexibility term expresses that a material does not have any bending stiffness. It is assumed that chains and steel cables have this feature. A catenary curve has physical and mathematical properties. Physically, the curve taking shape due to its own weight of the material is resulting in a physical equilibrium state where its potential energy goes the lowest level. Mathematically, in the Cartesian coordinate system, the distance of this curve to the z-axis can be found with Eq.1.1.

$$y = a \cdot \cosh\left(\frac{z}{a}\right) \quad \text{(Eq. 1.1)}$$

When a catenary curve is revolved at the distance **r**, the obtained surface is called “catenoid”. (Figure 1.2.b) This formed surface has an anticlastic form and minimal surface geometry. In figure 1.2.c, there is a minimal surface example obtained using the Surface Evolver 2.70 software. The **x** and **y** length was measured as 12.9, at the "**z = 0**" point of the minimal surface obtained from the software.(Figure 1.2.c) This result is consistent with the mathematical expression of the catenary curves.

$$a \cdot \cosh\left(\frac{10}{a}\right) = 17 \rightarrow a = 12{,}9 \quad \text{(z=10 h/2 of catenoid)} \quad \text{(17 is radius of catenoid at the point z=10)}$$

$$x = y = \left(12{,}9 \cdot \cosh\left(\frac{0}{12{,}9}\right)\right) = 12{,}9 \quad \text{the distance of catenoid at the point z=0}$$

1.3 Soap films and tensile membrane structures

Liquids have surface tension energy. Because of this energy, the water surface acts like a stretched elastic membrane. For this reason, it is possible that a denser metal object than water can stays on the water surface without sinking. Due to the principle of minimum energy, surface energy tends to be minimized. The potential surface tension energy present on the surface is proportional to the surface area. The reduction of surface energy is possible by the reduction of surface area. The surface energy is the amount of energy required to expand the surface area per unit.

Within a three-dimensional frame that immersed soapy water, a surface with the minimal area is formed. By virtue of this surface form, potential tension energy of the soap film surface reduces to the minimum level. This surface is the one having the possible smallest surface area of that can be created within that frame. That surface is called minimal surface. It is the result of the equilibrium state that the surface physically creates. It is assumed that the soapy water surface does not have a shear resistance. The combination of the surface tension and the zero shear stiffness causes mathematically and physically special surfaces. The minimal surfaces have structural properties because of its equilibrium state.

A minimal surface can be applied as a tensile membrane structure, because of the equilibrium state it has. However, the design possibilities of membrane form provided by soap films are limited. This is because its surface tension is the same in both directions. Generally, for architectural or structural reasons, the stress distribution on the surface need to change to develop the surface capability.

Minimal surfaces are anticlastic, its K value is smaller than zero. The directions of the surface principal curvatures are opposite and same magnitude. The mean curvature on a minimal surface for all points is zero. (Figure 1.3) Mean curvature is half of the sum of the principal curvatures at a certain point on the surface.

A soapy water bubble cover an air mass with the minimum surface area so reduces the surface energy to the least. The sphere is the lowest possible surface area surrounding a certain amount of air mass. The spherical surface is synclastic, the direction and value of principal curvatures are same. K value is greater than zero. So, the sphere is not regarded as the minimal surface mathematically. Because its mean curvature is not zero.

"The art of lightweight membrane architecture started with Frei Otto's soap film experiments in the 1950's. Finding form by using self-forming processes was the philosophy of the new design school he founded. He developed the building of modern tensioned membrane structures based on the concept of 'minimal surfaces'. These are defined as having the smallest surface areas requiring the least amount of potential energy due to their form within a particular set of "boundaries". Their main structural characteristic is that of having a uniform stress distribution throughout." [DG]

1.4 Form-finding

Tensile membrane structures consist of surfaces with two directional curvatures. A tensile load is applied to the surface, so the surface gains stability due to this tension load. The curvature of the surface ensures the distribution of the prestresses on the surface. The desired force distribution does not occur on a surface where the required curvature is not present, therefore the surface does not gain a structural property. On the same surface, the curvature that in two opposite directions is the most fundamental feature of the membrane structures. It is not possible to identify these surfaces with traditional architectural drawing techniques. These surfaces can be modeled by means of a material that will provide physically flow of force on the surface or software that mimics this force flow. This shape searching process is called form-finding. A soap film is the ideal physical material to determine this kind of forms because it is too thin and does not have a shear resistance.

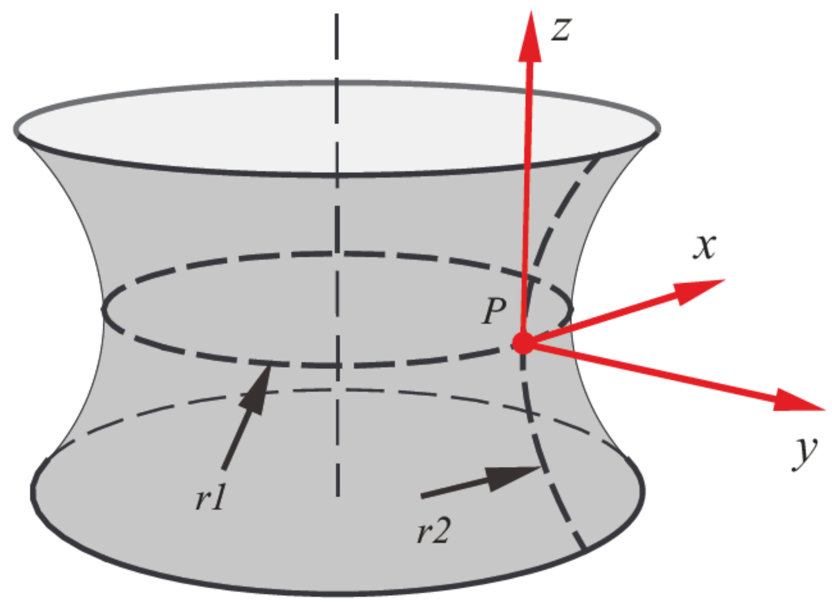


Figure 1.3 Catenoid
(Minimal surface formed between two parallel rings)

Principal curvatures $r_1 = -12{,}9$ $\quad r_2 = 12{,}9$

Mean curvature $M = \frac{1}{2} \cdot (k_1 + k_2)$ (Eq. 1.2)

$$M = \frac{1}{2} \cdot \left(\left(-\frac{1}{12.9} \right) + \left(\frac{1}{12.9} \right) \right) \rightarrow 0$$

The mean curvature is zero at point **P**, this is valid for all points on the surface shown in figure 1.3.

Form-finding is the process of creating an equilibrium surface within certain boundary conditions. This process aims to create an aesthetic, functional and structurally reasonable surface by revising the boundary conditions and the stress distribution forming the surface. The boundary conditions consist of edge elements of the surface and support points. The equilibrium form means that all points forming the surface are in a physical equilibrium state under the tensile load applied to the surface. When a tensile load is applied to a membrane surface, if there is a compression on the surface, wrinkles occur on it. This result indicates that the prestress is not properly distributed on the surface, so the surface is not in the equilibrium state.

Form-finding process is evaluated under two different concepts as the physical and numerical method.
The first examples of tensile membrane structures were designed using physical models. At that time, the physical models which prepared using soap films and flexible fabric pieces were used for manufacturing of the structures. In architectural sense, physical modeling is up to date. These models, which can be created quickly and economically before starting to numerical modeling, can provide more creative design solutions. Physical modeling may also be better from three-dimensional rendering to understand a complex surface.

Due to the invent of numerical modeling methods of membrane surfaces and developments in computer technology, the design, manufacturing, and analysis of these systems started to be done via computer. In the numerical form-finding process, the membrane surface is modeled as a mesh. Manufacturing and structural analysis processes are done on that mesh surface. The numerical form-finding process is independent of the physical properties of the membrane, like thickness or elasticity. The equilibrium surface is formed by using different numerical form-finding methods. That methods are Force Density, Dynamic Relaxation, and Finite Element Methods.

The use of numerical methods for the design and analysis of membrane building systems began with the Munich Olympic Stadium (1972) project. The Force Density Method, introduced by Klaus Linkwitz, was the first numerical method to satisfy specific needs of tensile structures, in 1971.[DR] Appendix 1 contains a numerical form-finding example using the Force Density Method for a four-point network.

Membrane surfaces can be expressed as fluid in the form-finding process. A membrane surface creates itself in the frame of given boundary conditions and the applied tensile load distribution. Our control possibility on a membrane surface geometry is limited to change boundary conditions and the ratio of tensile loads distribution on the surface. The forms created by these two variables is updated taking into account different criteria such as structural capacity, functionality and aesthetic compatibility. The changes we did on the form increases or decreases the structural capacity of the membrane surface. At this point, the priority is the structural sufficiency of the membrane surface against the loads which it will be exposed. The ability of the membrane to exhibit sufficient resistance to the loads comes before then its aesthetic appearance and functionality. In this context, snow load has critical importance. The reason for the priority of the structural resistance capacity is the limited mechanical property of the membrane material.

2. Basic forms

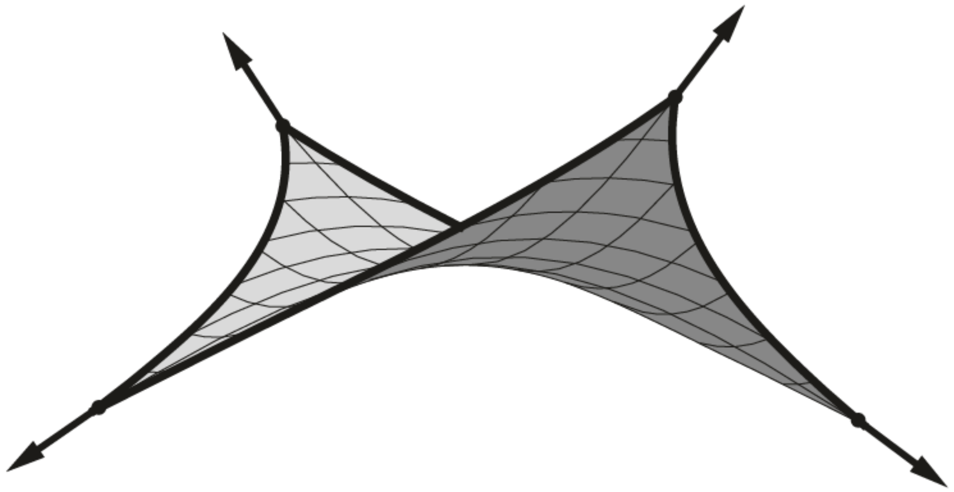


Figure 1.4.a Mechanically prestressed membrane structures (Anticlastic surface structures)

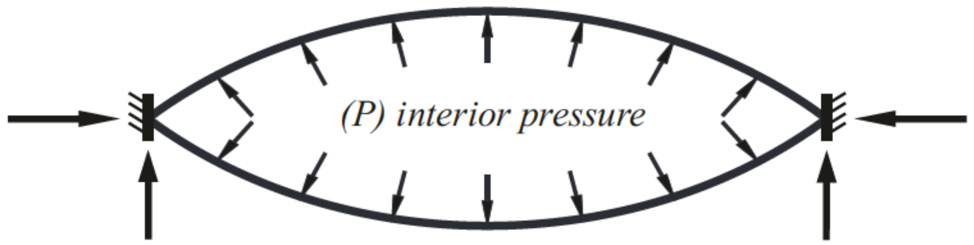


Figure 1.4.b Pneumatically prestressed membrane structures (Synclastic surface structures)

The load-bearing mechanism and capacity of the structure depend on the geometry of the surface, at the membrane structures. Membranes as a material, when compared with traditional building materials have a limited structural capacity. Its compression, shear and bending strengths are negligible. Membranes can only resist external loads by tensioning. This phenomenon requires that membrane building systems comply with a number of basic rules. The most basic rule is that the surface must consists of curvatures. The direction of these curvatures may be same or opposed. The second basic rule is that the surface must have a prestress. The prestress method applied to the surface depends on the Gaussian curvature of the surface form. Depending on the relationship between the form and the prestressing technique, the membrane structures are divided into two basic category.

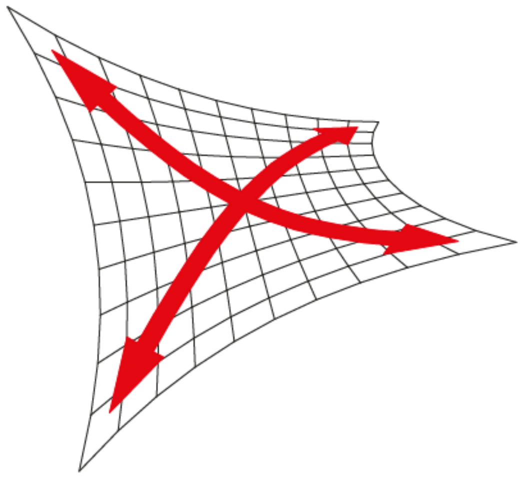
a) The systems that surface prestress provided mechanically

The form of membrane surface is anticlastic and its K values are smaller than zero. The surface consists of from two opposite curvatures. Hyperbolic surfaces is the basic structural form for a mechanically prestressed system. It is consist of at least four corner points, one of the points is in a position to give curvature to the surface. A surface consisting of three points is a flat surface at every possible location of corner points, so it is not a structural form. Steel cables are often used as edge elements on mechanically prestressed surfaces. Generally, the surface tension is provided by these cable elements.

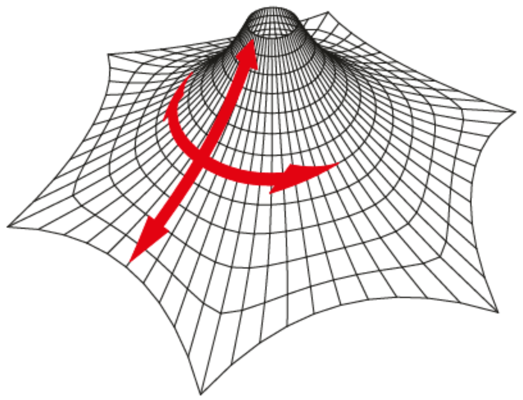
b) The systems that surface prestress provided by air pressure

The form of air supported membrane surface is often synclastic. Generally, its K values are greater than zero. The curvatures of the surface are the same in the both directions. To apply air pressure creates a tension on the surface. The applied internal pressure is higher than the external atmospheric pressure. A sphere is the most ideal structural form for pneumatic construction. Air pressure can be applied also on a cylindrical closed surface.

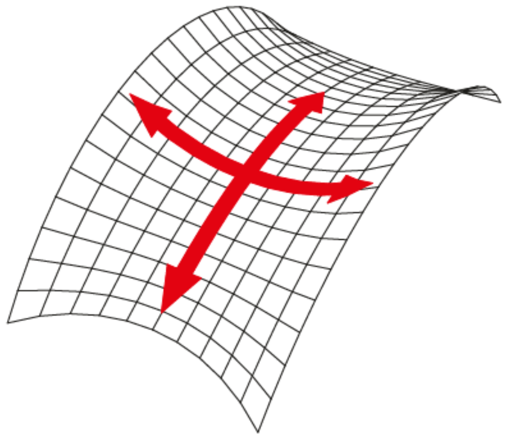
2.1 Anticlastic membrane forms



(a) Hyper form



(b) Conical form



(c) Arch form

Figure 1.5 Basic forms of mechanically prestressed membrane structures *(The red lines show the opposite curvatures of the membrane surfaces.)*

Mechanically prestressed surfaces are generally classified into four different types. All possible membrane structure surfaces are derived from combinations of these basic forms. Load bearing principles of all forms are the same. These forms' surface consists of opposite curvatures. Each form has different advantages in terms of architectural and structural design.

• **Hyper form:** Is the basic form for the mechanically prestressed membrane structures. Other forms include this surface. Hyper forms are architecturally rich. Their appearance varies greatly due to the perspective. This appearance diversity is not seen in a simple conic form. It requires careful planning, considering the rain and sun's rays, due to the height of the corners.

• **Conical form:** The surface gets opposed curvature with an elevation in the center of the surface. The low elevation at the edges increases the functionality of the structure. It provides greater protection against rainwater and sun rays. When compared it with other forms, it has larger volume. If a membrane structure is to be exposed to high snow load, conical form preferable because of its high surface slope. A larger covered space than the hyper form can be provided with conical forms.

• **Arch form:** The membrane surface gains curvature with a curved beam that passes through sides or the middle of the surface. A wide span without mast can be build with the arch form. The arch forms are more stable because the membrane surface is supported by a load bearing construction. The arch beam which giving the membrane its curvature is singular, parallel or it may have a circular array settlement.

• **Ridge valley form:** Prestress on the membrane surface is produced by means of steel cables tensioning in the opposed direction. It has a zig-zag look. Its surface curvature is relatively less when compared with other forms. This form can be regarded as a derivative of the hyper form.

A same membrane surface can be carried with different construction techniques. In this context, the hyper and conical form surfaces are independent of the load bearing construction. Middle elevation of a conical form can be carried by a mast from inside or by hanging to a beam that rising from outside. The load bearing arch beam is part of the arch form. The arch form takes its surface geometry from the carrier arch beam. The same condition is valid for ridge valley form, the cables are part of the membrane surface geometry. That surface form can only be provided by these cables.

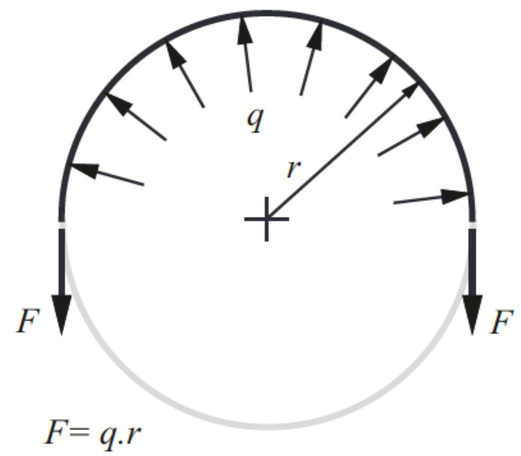
Tensile membrane structures can be examined in two separate parts as membrane surface and load carrier construction. Stresses on the membrane surface are transferred to the load carrier system. Membrane surface and load carrier system is a whole in architectural and structural context. A membrane structure may be independent or part of a building system. In case of being a part of a building system, a designed membrane surface which satisfies all the necessary conditions may be not applicable and/or nonfunctional when the load carrier system is incorporated into the whole building. When defining a membrane surface, it is necessary to take into account the invisible parts of the surface forms. The loads formed in the masts are transmitted to the foundations via the transfer cables. Since the transfer cables have a certain angle, they require additional area that increases or decreases depending on the mast height. In a tensile membrane structure that supported by the cables, all the loads on the surface are carried by the foundations. Therefore, tensile membrane structures require relatively large foundations. While defining a membrane form, the suitability of the installation area to this kind of secondary elements must be taken into consideration.

2.1.1 Curvature and tension

The stress generated on the surface of a cylinder is equal to the multiplication of the radius of the cylinder and the applied distributed load. This equation is known as the boiler pressure formula. The stresses occurring on the surface or edge cables in a membrane can be estimated with this formula. If it examined deeply, we can better understand why we are needing curvatures on a membrane surface.

Boiler formula for a line $F(kN) = q\ (kN/m) \cdot r\ (m)$ (Eq. 1.3)

Boiler formula for a surface $F(kN/m) = q\ (kN/m^2) \cdot r\ (m)$ (Eq. 1.4)



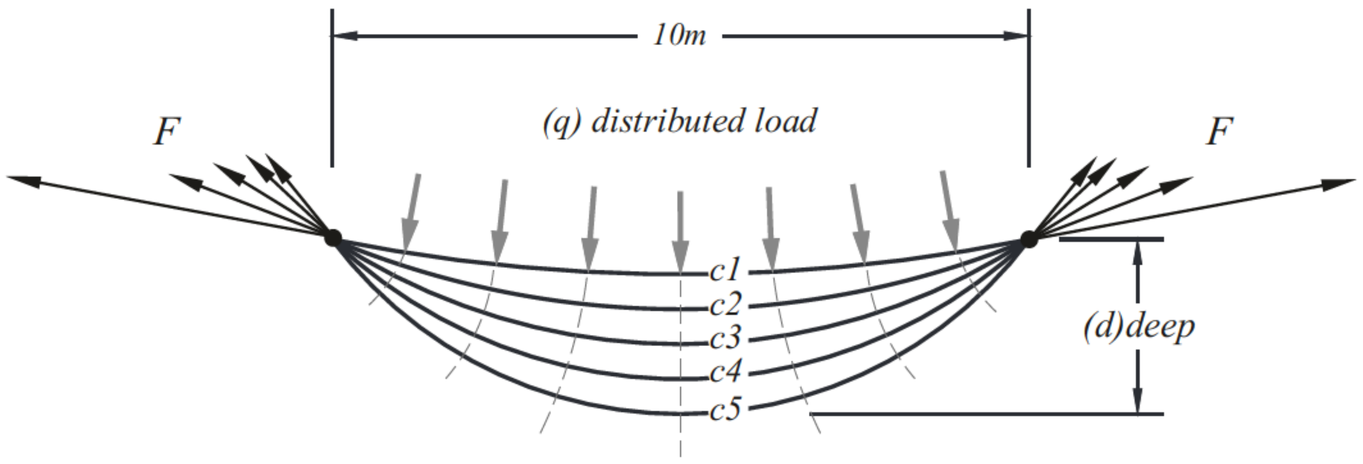
F= q.r

F : tension
q : distributed load
r : radius

Figure 1.6 The boiler pressure formula

There are five curves with different radii in figure 1.7.a. The depth difference between the curves is 50cm. Suppose that these curves are different alternatives for the edge cable of a mechanically prestressed membrane surface. In this case, the distributed load (q) represents the surface prestress. For example, if the prestress we need to obtain on the membrane surface is 1kN/m, the force required to apply to the cable on the **c1** curve is 25kN. But, it is sufficient to apply 13kN force to the cable at the **c2** curve to get the same prestress on the surface. The force required to apply to the edge cable to achieve the same prestress on the membrane surface is less due to the increased curvature depth. (The area difference between curves **c1** and **c2** is 3.5m².)

Let's suppose that the curves in the figure 1.7.a represent an anticlastic membrane surface sections. In this case, the distributed load (q) represents a wind load that affects the surface. If we adjust the units for a surface, (Eq.1.4) the result gives surface tension. The figure 1.7.b shows the relationship between curvature depth and surface tension.



Curve	c1	c2	c3	c4	c5
(d)Deep	0,5m	1m	1,5m	2m	2,5m
(r)Radius	25,25m	13m	9,1m	7,25m	6,25m
(q)Load	1kN/m	1kN/m	1kN/m	1kN/m	1kN/m
(F)Tension	25,25kN	13kN	9,1kN	7,25kN	6,26kN

Figure 1.7.a Five different curves are exposed to the same distributed load (1kN)

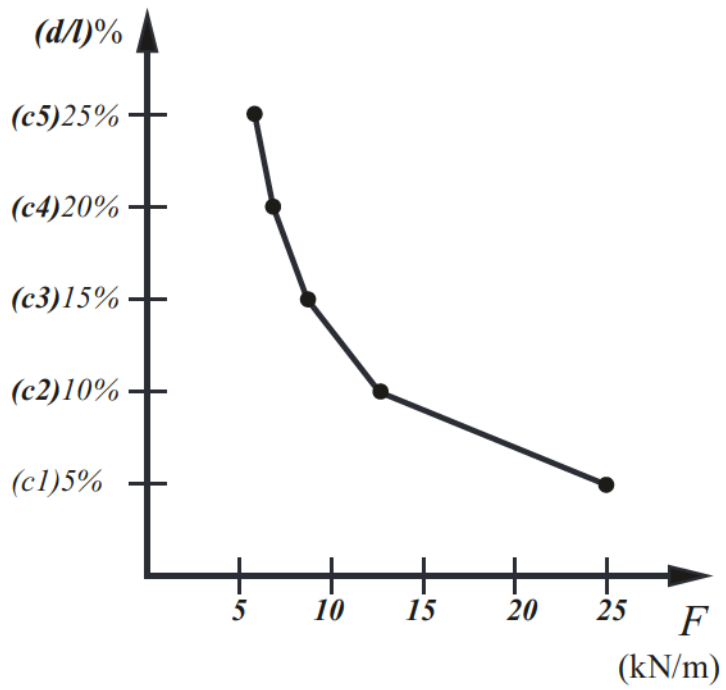


Figure 1.7.b The curve deep and tension relation (As the curve depth increases, the surface tension decreases.)

2.1.2 Form and prestress

A mechanically prestressed membrane structure surface consists of opposite curvatures. The stresses happening on the surface are carried in the direction of these curvatures as a tensile load. The deep of the curvatures forming the surface and their ratio to each other determines the load carrying capacity of the surface. As the curvatures increase, the load carrying capacity of the surface increases. The prestress distribution on the surface depends on the ratio of these curvatures to each other. As the curvatures on the surface increase, the amount of prestress required for stability decreases.(Figure 1.7.b) The prestress, gives stability to the membrane surface. The prestress is a permanent load. An excessive prestress reduces the lifetime of the membrane material due to creep behavior in polymeric membranes. The high amount of prestress, also requires to increase the cross-section of the load carrying construction profiles.

The minimum amount of prestress for PVC/PES membranes cannot be less than 1.3% of the breaking strength of the membrane. The lowest prestress value for PTFE/-Glass membranes is 2.5kN/m. These values are valid for both directions of the membrane.[DG] The applied prestress to the membrane surface decreases with time. The initial prestress that applied to the membrane surface, should be capable of providing surface stability throughout entire use of the membrane. A membrane surface is exposed to snow and wind loads. Due to these loads, the stress on the membrane surface may increase 6-10 times. For this reason, the amount of prestress applied to the surface must be 1/20 of the breaking strength of the membrane.[LW] Table 1.1 shows the recommended lowest prestress amounts for PVC/PES membrane materials.[DG]

The rate of curvature is constant on a minimal surface. This properties leads to an isotropic stress distribution on the surface. Some minimal surfaces are the typical forms of the mechanically prestressed membrane structure. Due to architectural or structural reasons, the curvature distribution on the surface may need to be changed in a different rate. In the form-finding stage, if the rate of the prestress distribution on the surface changed, a new equilibrium surface constitutes. Consequently, the surface geometry changes. In case the stress changed in the same rate on the surface in both directions, the surface form continues to stay in the same geometry. Because the same equilibrium state of the surface still continues. But, the amount of the stresses on the surface changes.

Membrane Type	Type 1	Type 2	Type 3	Type 4	Type 5
Min. Prestress	0.70kN/m	0.90kN/m	1.30kN/m	1.60kN/m	2kN/m

Table 1.1 Minimum prestress levels for PVC coated polyester membrane structures (Source: [DG])

2.1.3 Prestress distribution and curvature ratio

The equilibrium state of a membrane surface is estimated by the following equations

$$P = \frac{q_1}{r_1} - \frac{q_2}{r_2} \quad \text{(Eq. 1.5)}$$

P : Surface pressure

q1, q2 : Surface tension

r1, r2 : Surface curvature radius

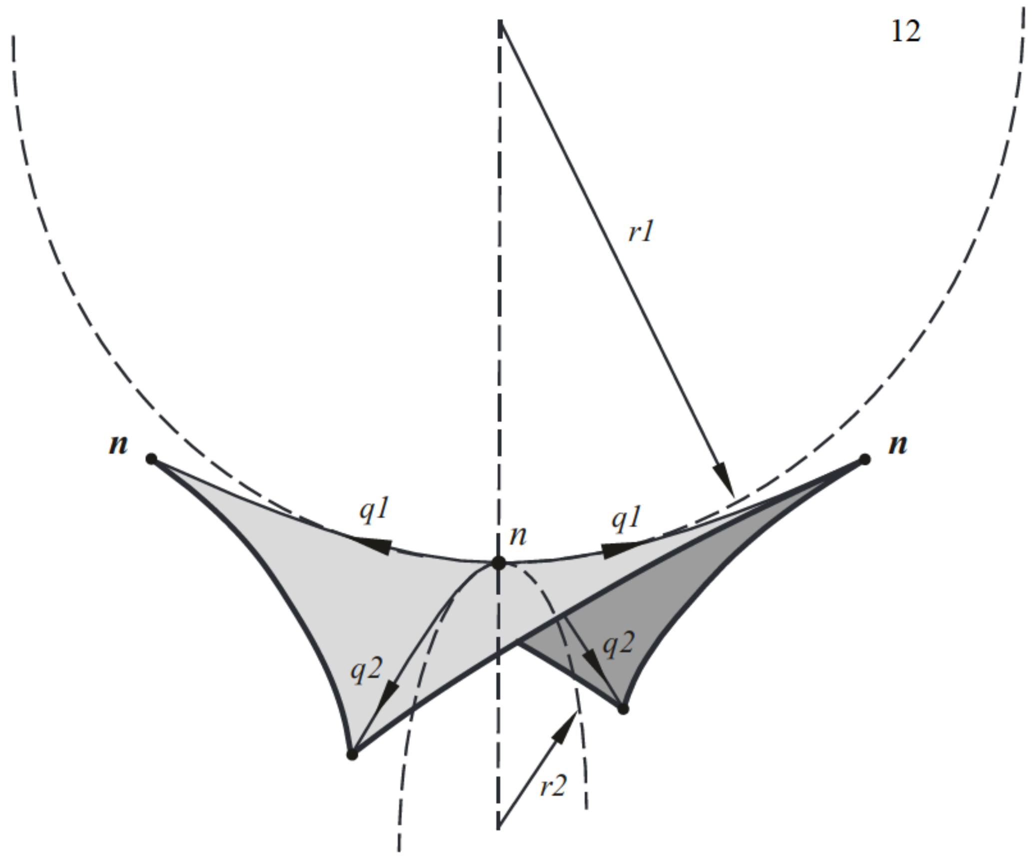
If there is no pressure on the surface

$$\frac{q_1}{r_1} = \frac{q_2}{r_2} \quad \text{(Eq. 1.6)}$$

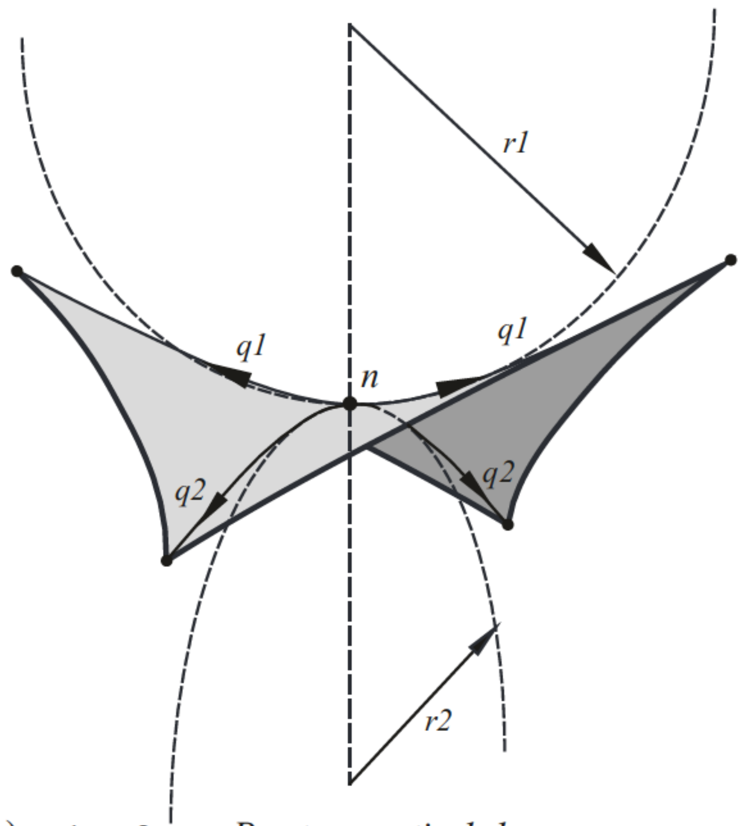
During the form-finding process, the loads that will affect the membrane surface are considered. In that process, the basic target is that the structure will provide maximum strength and stability against wind and snow loads. For this purpose, it is often necessary to change the ratio of the curvatures forming the membrane surface. Furthermore, the reason for changing the ratio of curvatures may be aesthetic or functional requirements. According to the Tensinet Design Guide, prestress rates on the membrane surface usually vary between 1: 4 and 4: 1.[DG]

In figure 1.8 there are two hyper forms that anchored at the identical points, with different surface curvature ratios. In figure 1.8.a, the radius of **r1** is twice the radius **r2**. These two different curve distribution ratio leads to two main structural consequences. Firstly, the prestress in the **q1** direction is two times high from the **q2** direction. Secondly, the reactions at the support points "**n**" are higher. The hyper form shown in figure 1.8.b is theoretically minimal. On a minimal surface, the ratio of these curvatures to each other is equal for entire surface. Hence, on a minimal surface, the prestress is the same in both directions at a given point. In figure 1.8.b, the reactions coming from prestressing are the same at all support points.

Hyper and arch form can be designed minimally. But, at a conical form, the radius of curvature is larger in the vertical direction. Consequently, surface tension is lower in the horizontal direction.



(a) $r1 = r2 \cdot 2$ *Prestress ratio 2:1*



(b) $r1 = r2$ *Prestress ratio 1:1*

Figure 1.8 Prestress and surface curvature

2.1.4 Geometrical nonlinearity

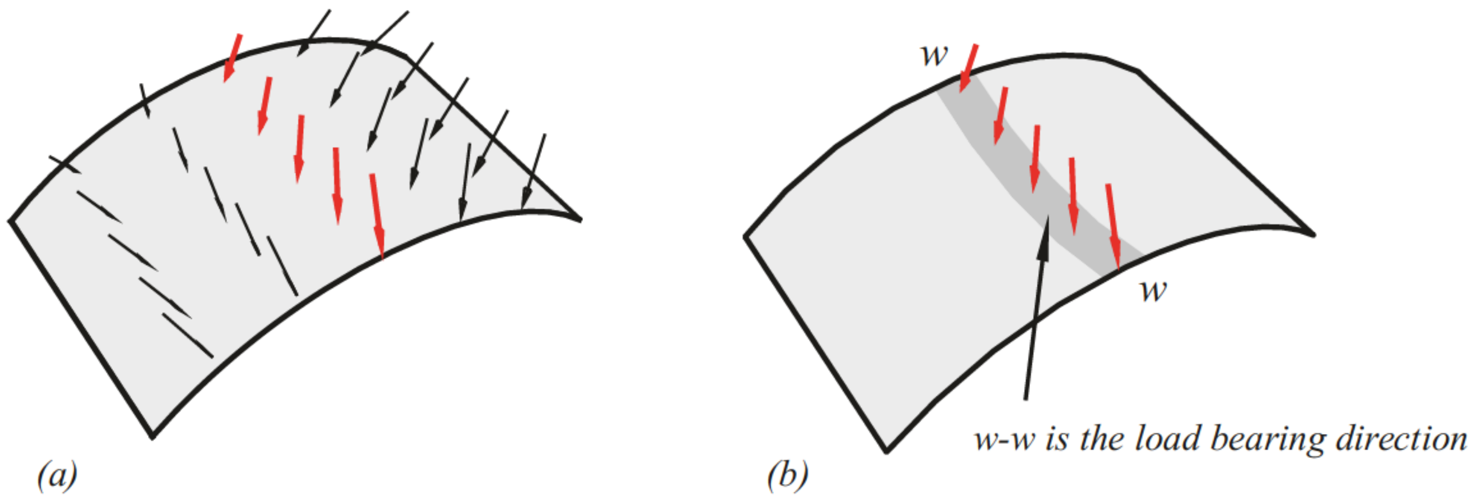


Figure 1.9 The membrane surface under the wind pressure

When a force acts on a structural system, if the geometry of the system does not change in a quantity that changes the reaction results, this system is assumed to be linear. In these systems, it is not need to recalculate the strain that occurs as a result of stress. Membrane surface shows great geometric deformation under load. Due to this geometric change, the stresses in the system must be recalculated according to the new geometry. Such kind of structural systems are called geometric nonlinear systems. Tensile membrane structures are the geometric nonlinear systems. Stress and deformation are recalculated depending on the strain. The softwares used in the structural analysis of the membrane structure get the results considering the geometric change. The calculation operation to be done in the divided into a certain number process step. The stress and strain are recalculated depending on the geometric change that occurring at each process step. As the number of calculation step increases, the results becomes getting more realistic.

Let's think an arch form fixed to the rigid profile, its whole surface exposed to the wind pressure. (Figure 1.9.a) The stresses on this surface occur in the **w-w** direction. (Figure 1.9.b) This stress on the surface can be estimated by using the boiler formula. This estimation is valid only for the initial condition. In reality, the surface tension changes due to the deformation of the surface. There is a surface tension estimation by using the boiler formula taking into account surface deformation, in figure 1.10.

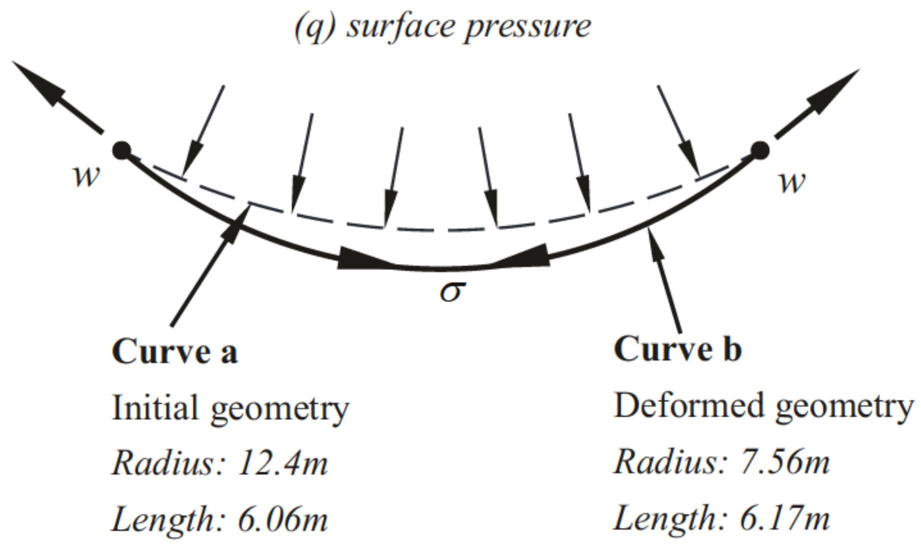


Figure 1.10 1m width membrane strip under the wind pressure. The surface stresses changing due to new geometry

$q:$ *Surface pressure* $0,7kN/m^2$

$r:$ *Curvature radius* $12,4m$

$E:$ *Elastic modulus* $500\,kN/m$

$W:$ *Membrane strip width* $1m$

$$\sigma = q \cdot r \rightarrow 0,7 \cdot 12,4 = 8,68kN/m$$

$$dL = \frac{\sigma \cdot l}{E \cdot W} \rightarrow \frac{8,68 \cdot 6,06}{500 \cdot 1} = 0.11m$$

(dL) New curve length $6,17m$

New radius: $a\sin\left(\frac{6/2}{r}\right) = \left(\frac{6.17/2}{r}\right) \rightarrow r = 7.56m$

Current tension $\sigma = q \cdot r \rightarrow 0,7 \cdot 7,56 = 5,29kN/m$

2.1.5 Surface deformation due to ponding

In an interior application, a membrane surface carries only its own weight. In a such kind of application, we can determine the surface geometry without a form constraint, to provide the desired visual effects and function.

The aim of the limitations imposed on the membrane surface is to increase the load carrying capacity and to prevent the negative effects of the deformation on the structure. Membrane structures are exposed to the snow and wind loads. A membrane structure must maintain its strength and stability under these loads. The geometry of a structural system changes when it is exposed to an external load. In the traditional building systems, this change is small not to be seen. However, deformation of tensile membrane structures is considerably large under the external loads. In a traditional building system, the section of the load bearing construction is determined according to the amount of loads. Theoretically, the section properties is unlimited in the that building systems. But, for the membrane structures, the structural capacity of the membrane material is very limited.

The modulus of elasticity indicates the amount of elongation of a material under the tensile load. Membranes have a low modulus of elasticity compared to conventional building materials. This is a fundamental criteria that determines the structural limit of the design of tensile membrane structures.

It is expected that the deformation will disappear on the membrane surface when the load is left. This depends on the geometry of the membrane structure surface. A membrane surface that deformed by snow load maybe fills with melt snow water. In such a case, the load becomes permanent and causes a serious risk to the entire membrane structure.

Let's think two hyper form, their all properties like prestress, material, projection area, applied load are same but their curvature is different. (Figure 1.11) The applied same load will result in different deformation.

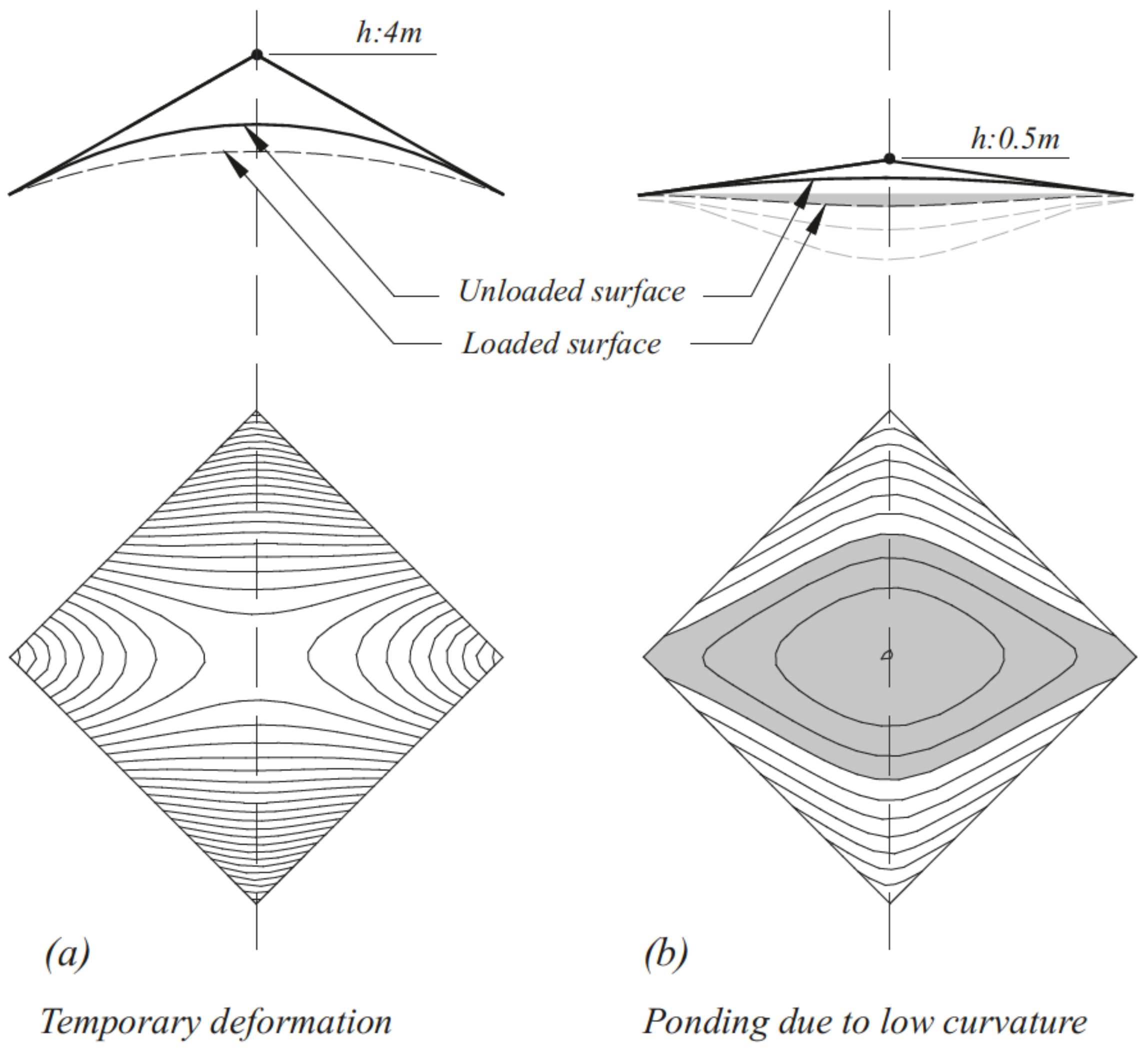


Figure 1.11 10x10m rigid edge hyper surface. High point **a**: 4m, **b**: 0.5m

The figure was prepared to explain the critical results of the deformation. The properties of two structure are same except curvature. But, the structural behavior under the load led to completely different results.

In figure a: It is expected that to be disappearing of its deformation when the load removed.

In figure b: The load and deformation become permanent due to the ponding on the surface. The deformation continues to increase because of collected water on the surface. The structure may collapse due to this unpredicted load at the form-finding and structural design stage.

2.1.6 Surface deformation due to fluctuation

A membrane surface is an entire part, though in a small area an unexpected stress and deformation may constitute a danger to the entire structure. A membrane structure surface consists of curvatures of varying radius depending on the form. The radius of curvature at the membrane edge regions is increasing so the surface getting flattened in that area. The less inclination in these regions creates a risk due to snow and rainwater.

The effect of the wind load on the membrane structure depends on the geometry of the membrane surface. Due to the sudden shape change in the membrane edge, the wind effect is critical in that flat regions. The wind creates fluctuating on the insufficiently curved and prestressed regions of membrane surface. This fluctuation reduces the economic life of the membrane. The Tensinet Design Guide recommends the maximum spanning as 20m, for the cable terminated membrane edge taking into account fluctuation effect. It also proposes that the surface can be checked with the equation shown in the Eq.1.7 against fluctuations.[DG] According to Seidel, if there is not enough prestress on the surface, the wind load can make a dynamic effect due to the fluctuating and may cause the collapse of the building.[SD]

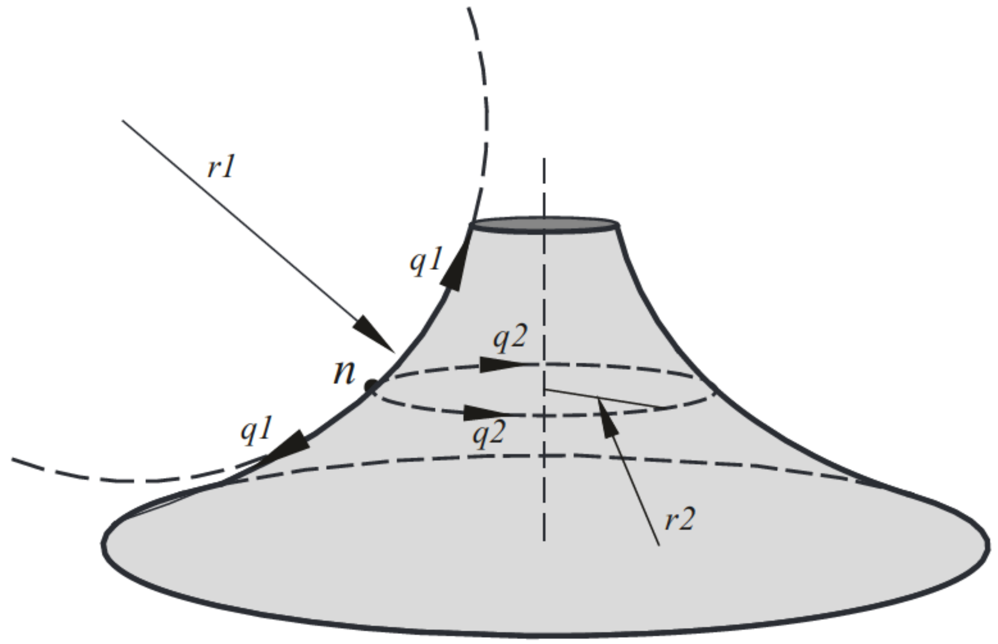
$$D \approx \frac{N_{Warp}}{R_{Warp}} + \frac{N_{Weft}}{R_{Weft}} \qquad \text{(Eq. 1.7)}$$

N_{Warp} : Prestress in warp direction (kN/m)
N_{Weft} : Prestress in weft direction (kN/m)
R_{Warp} : Positive radius in warp direction (m)
R_{Weft} : Positive radius in weft direction (m)
D : Stiffness of surface (kN/m^2)

D is greater than 0.3 (kN/m^2) on a stable membrane surface.

Fluctuation occurs on a surface around $D = 0.15(kN/m^2)$

Source [DG]



$r1 = r2 \cdot 2$

Figure 1.12 Conical form curvature

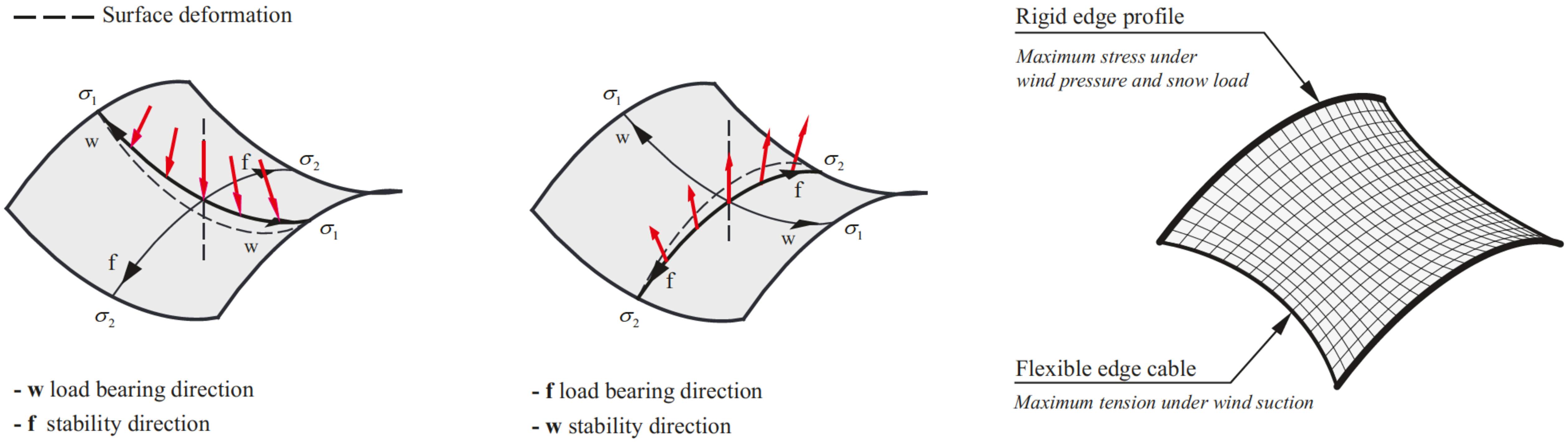
If the following values are accepted for the ***n*** point shown above on the conical surface

N_{Warp} : $3\ kN/m$ $\quad N_{Weft}$: $1.5\ kN/m$
R_{Warp} : $12m$ $\quad R_{Weft}$: $6m$

The surface stability check against wind fluctuating for point ***n***

$$D \approx \frac{3}{12} + \frac{1.5}{6} = 0.5 kN/m^2 \rightarrow 0.5 > 0.3\ kN/m^2$$

2.1.7 Surface curvature and external loads



(a) Wind pressure *(b) Wind suction* *(c) Load effects on the edge elements*

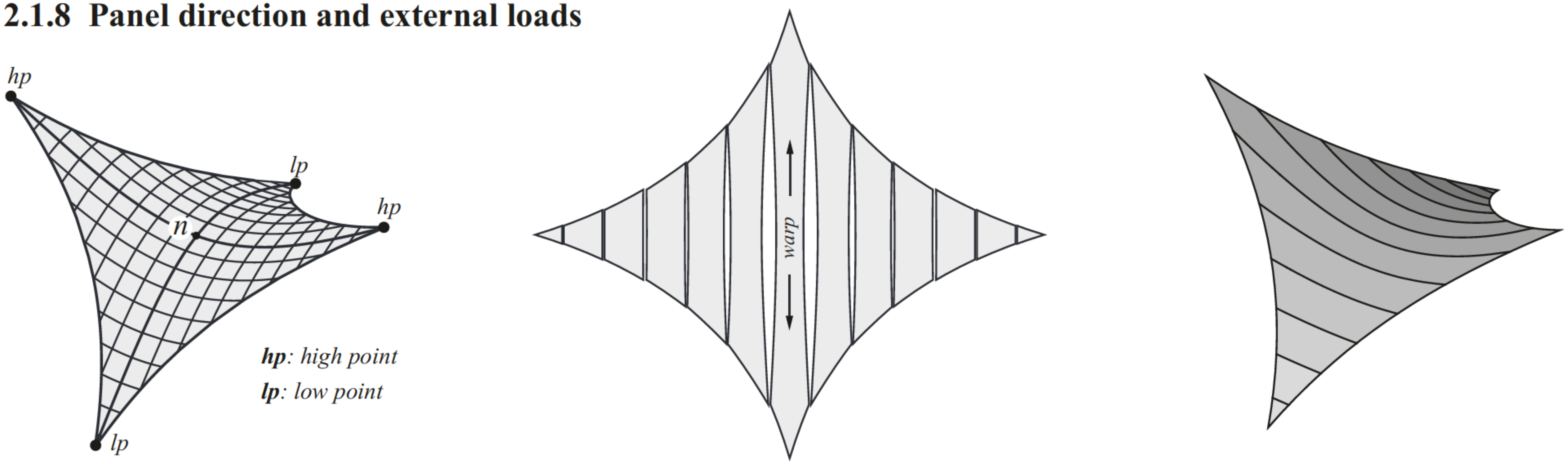
Figure 1.13 The influence of the surface curvature and load directions on the stress distribution

Loads acting on the membrane surface are carried in the direction of the curvatures forming the surface. The main loads that affect the surface are snow and wind loads. These loads affect the surface in different directions. The effect of the loads on the surface changes due to the geometry of the surface.

The figure 1.13.a and b show a piece of an anticlastic membrane surface. Stress and deformation on this surface vary according to the direction of the load. The surface in figure a is exposed to wind pressure. The curvature in the **w-w** direction carries this load. Under this load, the highest stress occurs in the direction of the **w-w** curvature. The same result is obtained also when snow load is applied to the surface. The wind direction is negative on the surface in figure 1.13.b. In this load case, the curvature in the direction of the **f-f** carries the load, consequently deformation occurs in this direction.

There is an arch form in figure 1.13.c. The practical consequence of the relationship between the load direction and stress distribution is shown in this figure. It is expected that the tension happening in the edge elements of the system will change according to the direction of the load. Two edges of this system fixed to a profile. The membrane surface was terminated with a steel cable on the other two edges. Maximum bending stress in the edge profiles occurs at wind pressure and snow loads. At the same load case, tension on the cables is expected to decrease to the minimum level. The highest tension on the cables occurs when the wind is in the negative direction. In the case of this load, it is expected that tension decrease in the edge profiles to the minimum level.

2.1.8 Panel direction and external loads



(a) Designed 3D mesh surface *(b) 2d patterned surface* *(c) 3d welded membrane surface*

Figure 1.14 Evolution of membrane surface

A membrane structure surface is produced by combining several panels. The process of making the three-dimensional membrane surface into two-dimensional panels is called patterning. Panel directions affect the structural capacity of the membrane surface. The determination of the panel directions of the membrane surface evaluate in structural, aesthetic and cost aspects. During the panelling process, the mechanical properties of the membrane to be used in the project and the loads which the structure will be exposed are taken into account, firstly.

Membranes used in mechanically prestressed membrane structures are woven textile materials. Loads formed on the membrane surface are carried through yarns forming the fabric. The fabric is made up of two yarn perpendicular to each other. These two directions of the fabric are warp and weft yarn. The physical properties of a membrane are different in these two directions. The membrane in the warp direction has a higher modulus of elasticity. Consequently, a membrane is stronger in warp direction and shows less elongation under load. The direction of the roll of the membrane is the warp direction.

The directions of the panels forming the surface follow the principal curvatures of the surface. In this way, it is ensured that the tension on the surface is carried by the weave yarns. The principal curvatures of the hyper form shown in figure 1.14.a are in the **hp-hp** and **lp-lp** directions. The surface can be divided into panels in these directions. During the structural design stage, the basic aim is that the warp direction is the same as curvature direction which tension is the highest. In this way, structural capacity of the surface increases, deformation under load is reduced. Let's assume that the snow is the critical load for the system shown in figure 1.14.a. So the curvatures in the **hp-hp** direction will carry the load. In case the panels are in **hp-hp** direction, the warp threads will carry the loads happening on the surface. In case the critical load is wind suction for the surface, the patterning in **lp-lp** direction increases the load carrying capacity of the membrane.

2.1.9 Panel width

If the **P** load applied to the "**a**" point of the flat membrane piece which consisting of **a, b, c, d** points, the shear stresses occurs on the surface. Depending on amount of stress, the surface deforms. This deformation is the shear strain. The Gaussian curvatures of the surface are zero at the initial geometry. The Gaussian curvature takes a negative value depending on the applied load and the shear capacity of the membrane. If the applied load exceed the membrane shear capacity, wrinkling occurs on the membrane surface. The shear resistance of the membrane used in the form-finding process is zero. The physical properties of the membrane are not taken into account during the form-finding phase, but shear properties are taken into account in the manufacturing process.

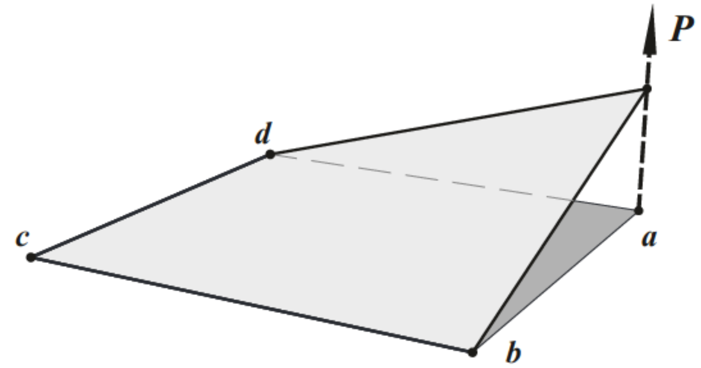


Figure. 1.15.a
A piece of membrane forced to deformation

When a three-dimensional surface is converted to the two dimensions, the surface becomes deformed. The amount of deformation in a panel depends on the Gaussian curvature of the surface. As the panel width increase on a membrane surface, the amount of required deformation increases. A prestress is applied during installation process to the surface which formed by joining two-dimensional flat membrane panels. Due to this prestress, it is expected that the membrane will form the form-finding stage surface geometry by occurring deformation. If the panel does not provide the required deformation under applied prestress, the membrane surface will have a polygonal appearance. In order to get a membrane surface which formed with smooth curvatures, the width of the panels must be within the deformation limits of the membrane material. The formula found in the Eq.1.8 was taken from IASS Technical Papers. This formula is recommended for calculating the maximum panel width.[HG] The shear resistance of the membranes is different. The PVC/PES membrane is more suitable than the PTFE/Glass membrane to produce a membrane surface with a high curvature.[BR]

$$w_m = \sqrt{\frac{-24 \times n_{px}}{Et \times k_G}} \qquad \text{(Eq. 1.8)}$$

w_m : Maximum panel width

n_{px} : Prestress in x direction (warp)

Et : Stiffness of membrane

$k_{G:}$: Gaussian curvature

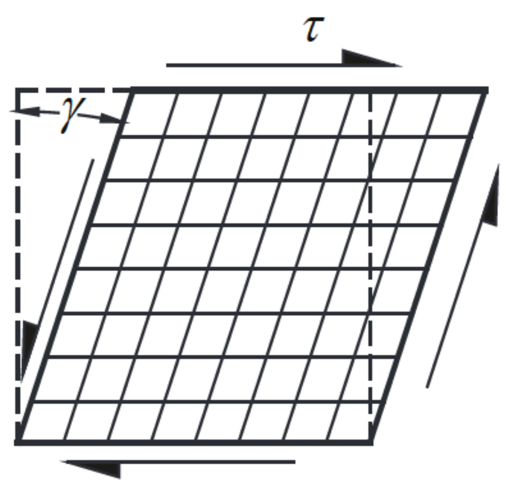
*If the following values are accepted for the **n** point shown figure 1.14.a,*

$r = 5m \quad (r_1 = r_2)$

n_{px} : *2kN/m* $\quad Et$: *600kN/m* $\quad k_{G:}$: *-0.04*

the max. panel width is 1.41m.

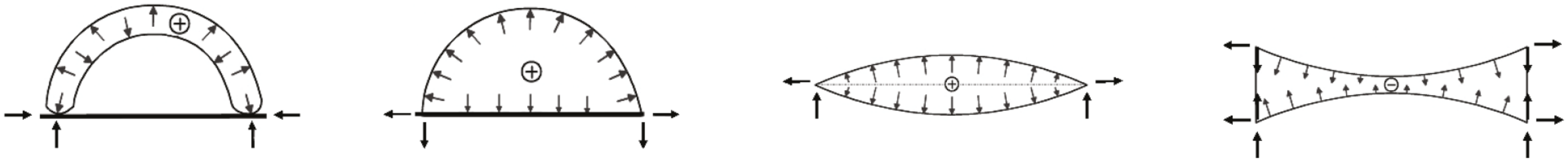
$$w_m = \sqrt{\frac{-24 \times n_{px}}{Et \times k_G}} \rightarrow \sqrt{\frac{-24 \times 2}{600 \times (-0.04)}} = 1.41m$$



τ : shear stress *γ : shear strain*

Figure. 1.15.b
Membrane shear stress and strain

2.2 Air supported structures



(a) Air beam *(b) Air hall* *(c) Cushion* *(d) Vacuum*

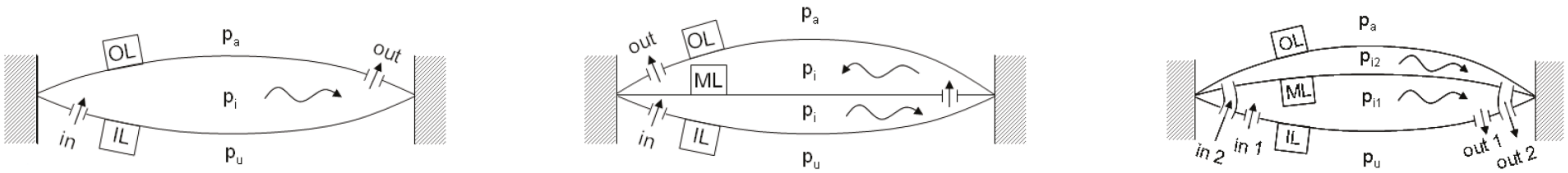
Figure 1.16 Basic forms of pneumatically prestressed membrane structures (Source [M1])

Air supported membrane structures usually consist of a synclastic surface. The principal curvatures of the surface are the same direction. For this reason, the K values are greater than zero. In the form-finding phase, it is intended to get a form where the prestress coming from internal pressure can be spread to the entire surface. The sphere is the best form in this context. However, this often fails to meet functional and aesthetic requirements. The basic membrane forms which surface prestress provided with air pressure are shown in figure 1.16.

Thanks to the air pressure applied to the membrane surface forming a closed area, the membrane surface gains design geometry. If the air pressure in the surface is equal to the atmospheric pressure, the form of the membrane surface is not stable. When the internal pressure applied to the surface exceeds the atmospheric pressure, tensile stress is generated on the surface. Due to this tensile stress, the membrane surface gains structural properties that can resist the external loads. The distribution of the prestress on the surface due to internal pressure, depends on the geometry of the form. Therefore, there is a relationship between surface stability and form.

• **Air-beam:** It is a one or two-dimensional load bearing elements. It has a cylindrical or derivative form. It requires higher internal pressure. The beam can be supported with steel cables. An air hall can consist entirely of air beams side by side.
• **Air Hall:** The membrane surface is fixed to a foundation that forming the border frame, gains prestress by air pressure. Membrane surface usually consists of one layer membrane. The inner pressure is higher than the outside atmospheric pressure. This pressure difference is not much to disturb the people inside. The doors are arranged so as not to lose internal pressure. The building is regularly fed by the air pressure supplier unit. It is used in sport, storage, temporary shelter areas.
• **Cushion:** Consists of two or more layers. The cushion edges are fixed to a construction. The stresses on the surface are transferred to the construction. It is used as a roof and facade covering element. Air-cushions are the most widely used pneumatic membrane structure system.
• **Vacuum:** The prestress on the membrane surface is achieved by vacuuming air inside the cushion.

2.2.1 ETFE Cushion



(a) Two layer cushion section

(b) Three layer cushion section middle layer mechanically prestressed

(c) Three layer cushion section middle layer pneumatically prestressed

OL= Outer layer ML= Middle layer IL= Inner layer in= Air inlet out= air outlet

Figure 1.17 ETFE cushion air management (Source [M1])

Air-hall and air-supported beams are usually independent structures. They do not need an auxiliary load carrying element. To use these systems as an architectural elements in a building has the limited solution potential. The air-supported cushion systems are different in this respect and they have rich possibilities in terms of architectural usage. It is often used as a facade and roof element in a building. Also, it is possible to apply it as an independent structure by means of a construction. The edges of the cushions are fixed to a rigid load bearing construction. Loads formed on the cushion surface are transferred to that construction.

Cushions are identified with ETFE material. The main reason for this is the superior optical and strength property of ETFE. Compared to mechanically prestressed woven membranes, the tensile strength of ETFE films is low. ETFE films demonstrate large deformation under load. Thermal conditions are influential on its mechanical behavior. The maximum span is limited because of these features. A facade to be covered with cushion is divided into small pieces. The mechanical properties of the ETFE are taken into consideration when determining the geometry of the pieces. According to Moritz, the span that can be passed using ETFE in the width direction is 4-5m.[M3] For a rectangular ETFE cushion, the longitudinal span is not a problem.[M4] ETFE cushions require a constant air pressure. These air support units are part of the structural system. These units are activated when the pressure in the cushion decrease. The operating frequency of the pressure support units is 50%.[AL] Each cushion forming the roof or facade has an air piping system consisting of flexible pipes. Through this installation system, the inner pressure of the cushion is kept under control, so the prestress is controlled. Depending on the external load situation, the pressure of the cushion is increased when necessary.

One of the most basic features of ETFE membranes is light transmittance up to 95%. The light transmittance is reduced when required by printing or coloring the ETFE material. An ETFE cushions consist of two or more layers. The middle layer is tensioned mechanically or pneumatically. If the middle layer pneumatically tensioned, its position is changeable. Depending on the geometry of the printing applied to the membrane, the light transmittance becomes under control, by changing the position of the middle layer. ETFE cushions provides high thermal insulation due to air between layers. The thinnest material is used as a middle layer.

2.2.2 ETFE Cushion and loads

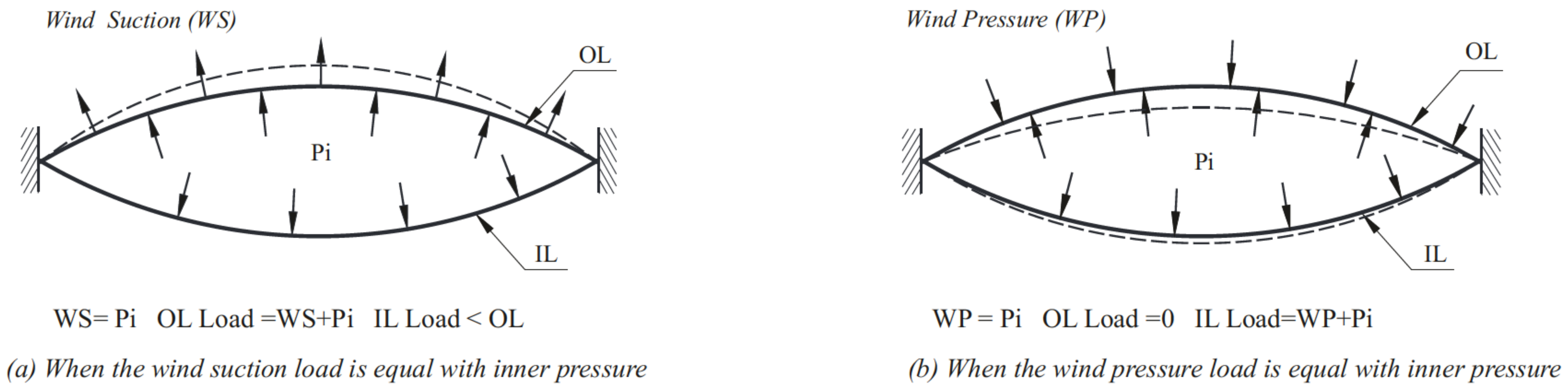


Figure 1.18 The effect of the wind load on the ETFE cushion layers

While an ETFE system is designed, the loads which the structure will be exposed are considered. Thermal conditions and speed of load affect the mechanical properties of ETFE. The characteristics of snow and wind loads are different. Snow is a long-term load and effects in cold weather. The wind is a short-term load, it can affect in hot or cold weather.[M2] A facade and roof of a building are not exposed to the same loads. There is a high wind load on the facades. The snow load affects only to the roofs. The amount of internal pressure, the geometry of the forms and the thickness of the material changes due to these loads.

To provide the necessary stability against snow and wind loads, the required prestress is 0.7-1.4kN/m².[M1] The internal pressure that must be applied to achieve the required prestress varies depending on the form of the membrane surface. The average prestress in the Allianz Arena Stadium is 1kN/m. The applied internal pressure to get this prestress value is 300Pa on the roof and 450Pa on the facades. In case of snow load, the pressure is increased to 800 Pa.[M3]

The upper layer of the ETFE cushion meets the load generated by wind suction. So, the top layer moves upward. (Figure 1.18.a) The volume of cushion increases because of this deformation. The reason for the enlargement is the strain caused by the tension in the upper layer. The air pressure must be raised to continue the prestress that exist on the membrane surface. Air support units cannot provide the required air pressure due to the sudden effect of the wind. The prestress reduces due to the decreasing inner pressure. Depending on the magnitude of the suction load applied by the wind, the prestress of the bottom layer may be lost. When the wind pressure affects the outer surface, if the wind pressure is higher than the inner pressure, the volume of the cushion decreases. (Figure 1.18.b) So, internal pressure increases. The tension disappears on the top layer. The wind pressure load is borne by the bottom layer.

The relationship between wind load and internal pressure is explained by the Boyle Gas Law. This law is "p x v = constant". (**p** is internal pressure, **v** is volume) When the wind suck, “**v**” increases and “**p**” decreases, in case compression, “**v**” decreases, “**p**” increases.

2.2.3 Synclastic surface and stress distribution

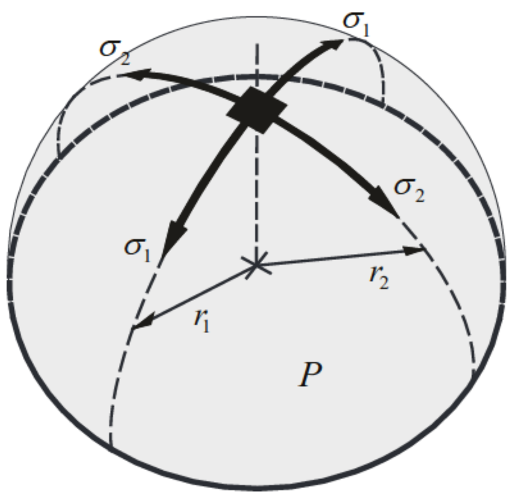


Figure 1.19 Stress distribution of the air supported spherical form

The stress distribution for a sphere which exposed to internal pressure can be found with the boiler formula below. On a spherical surface, the principal curvatures for all points are the same direction and value.

$r_1 = r_2$ $\qquad \sigma = p \cdot r \cdot 0,5$ (Eq. 1.9)

$r\ (m)$: Curvature radius $\quad \sigma\ (kN/m)$: Stress $\quad p\ (kN/m^2)$: Interior pressure

In case radius of surface curvatures are not equal,

$r_1 \neq r_2$ $\qquad \sigma_1 = p \cdot r_1 \cdot 0,5 \qquad \sigma_2 = p \cdot r_2 \cdot 0,5$ (Eq. 1.10)

The equality above can be written as in the below

$$p = \frac{\sigma_1}{r_1} + \frac{\sigma_2}{r_2} \qquad \text{(Eq. 1.11)}$$

The stresses distribution on the surface changes depending on the radius of principal curvatures. The principal stresses for an ETFE cushion are estimated at the right side, as an example.

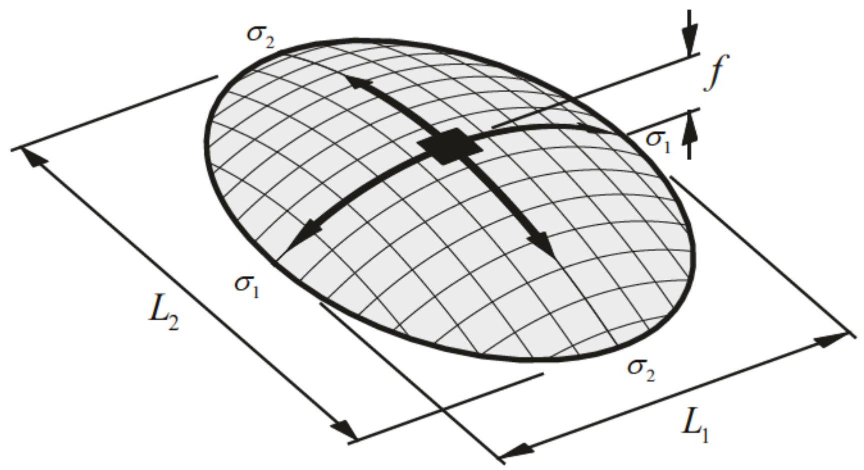


Figure.1.20 ETFE cushion

$p = 0.3kN/m^2 \quad L_1 = 6m \quad L_2 = 4m \quad f = 0.72m$

$$r = \frac{L^2}{8 \cdot f} + \frac{1}{2} \cdot f \qquad \text{(Eq. 1.12)}$$

$$r_1 = \frac{6^2}{8 \cdot 0,72} + \frac{1}{2} \cdot 0,72 = 6,61m$$

$$r_2 = \frac{4^2}{8 \cdot 0,72} + \frac{1}{2} \cdot 0,72 = 3,14m$$

$$\sigma_1 = p \cdot r_1 \cdot 0,5 \rightarrow 0,3 \cdot 6,61 \cdot 0,5 = 1kN/m$$

$$\sigma_2 = p \cdot r_2 \cdot 0,5 \rightarrow 0,3 \cdot 3,14 \cdot 0,5 = 0,47kN/m$$

Checking the results with Eq.1.11

$$p = \frac{\sigma_1}{r_1} + \frac{\sigma_2}{r_2} \rightarrow \frac{1}{6,61} + \frac{0,47}{3,14} = 0.3kN/m^2$$

Part II

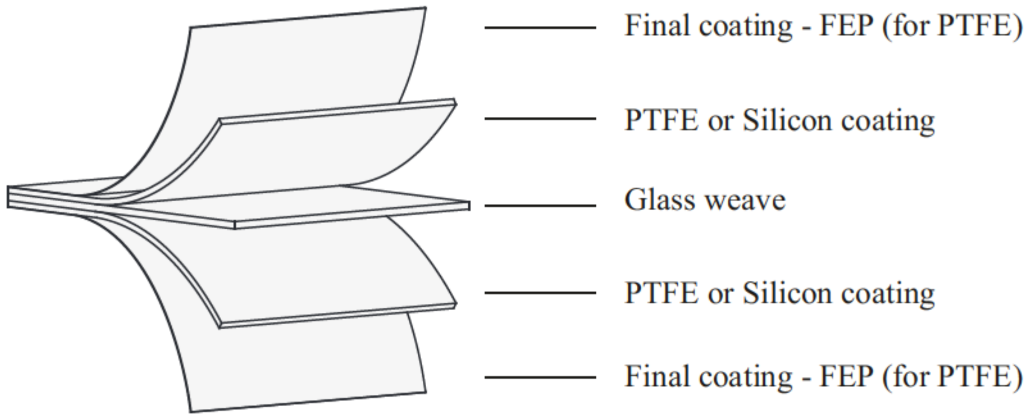
Materials

Frei Otto used canvas material as a membrane in his first project, in 1955. This material could not withstand high stress and environmental effects. Otto began to use synthetic materials in his later works. He used the membrane that was the glass fabric coated with polyurethane, in 1957. This membrane was not long lasting because it is affected by moisture. In the same year, he used polyamide in his project in Berlin. This material began to tear six weeks after installation. Otto used the first PVC coated polyester membrane in 1963. This material has become a standard for the tensile membrane structures since the 1970's.[KN]

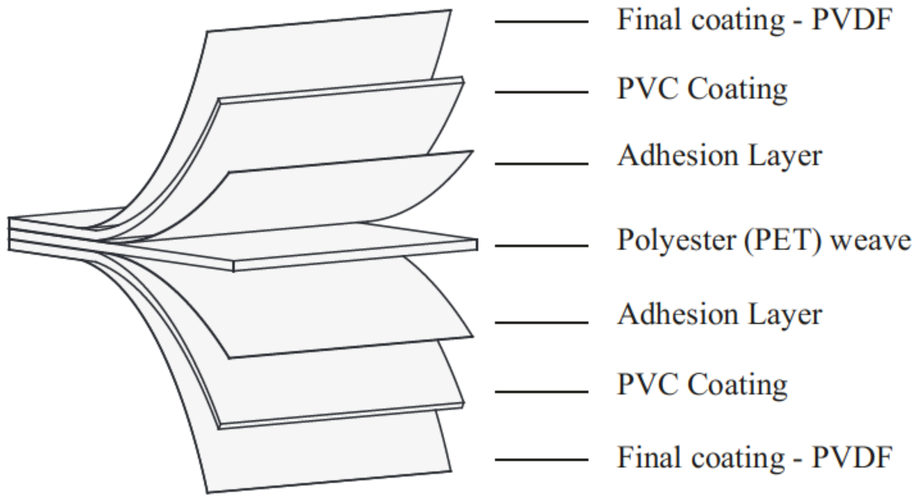
The structural limit for tensile membrane structures depends primarily on the possibilities offered by the material. This limit is constantly expanding, depending on the developments in technology and material science.

3. Membrane structure materials

(a) Single layer film



(b) PTFE or Silicon coated glass weave



(c) PVC coated Polyester weave

Figure 2.1 Membrane material components

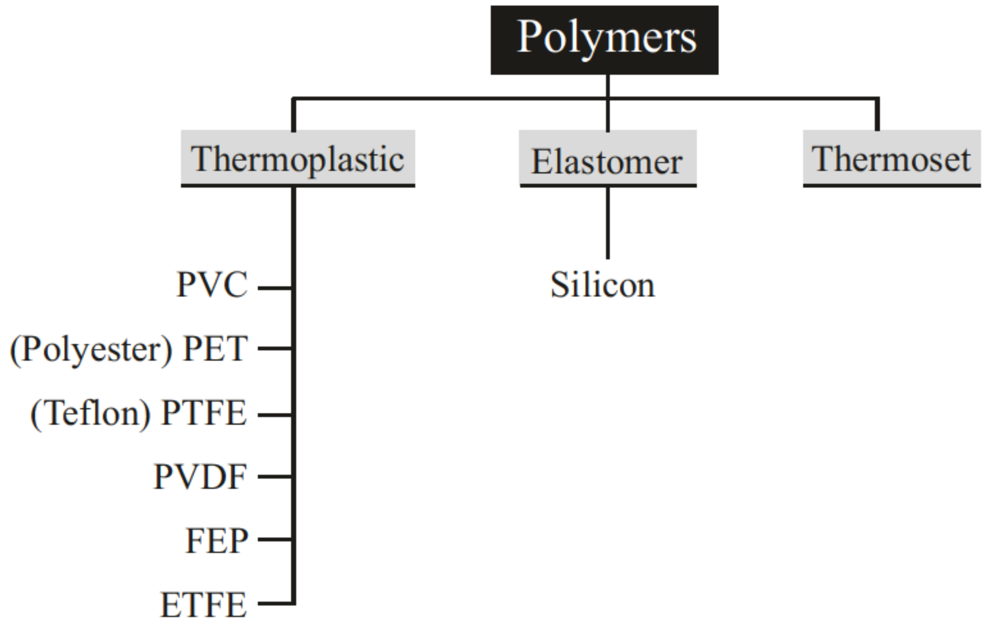


Figure 2.2 Simplified presentation of polymeric membrane materials

The figure 2.1 represents the components of the membrane structure materials which are commonly used. All of these materials are polymers except glass. All off them have different advantages and disadvantages in a different context. They are assembled to provide the superior features needed by tensile membrane structures. By completing each other's deficiencies, they provide a strong and durable material in total. It is impossible to think a tensile membrane structure without these materials.

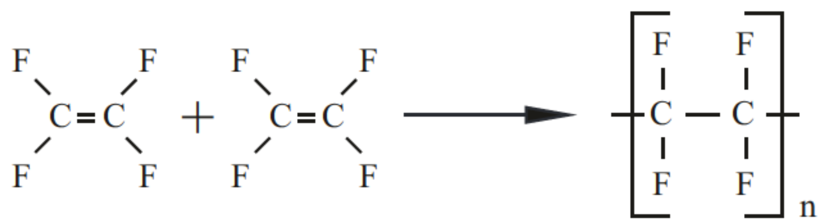
3.1 Polymers

The mechanical behavior of a structural material under load is not independent of its micro-structure. The knowledge about micro-structure of a material is necessary to understand its behavior under mechanical and environmental effects.

Polymer means multi-unit. It consists of the words "mer" which means unit, and "poly" which means multiple. Polymers are structures made by repeating the same unit. Each unit consists of a group of atoms or a group of molecules. These groups are in a chain shape. Each unit that forms a polymer is called a monomer. Monomers are converted into the whole united material by the polymerization process.[AK], [W1]

A polymer may be natural or artificial (synthetic). Natural polymers are structures that are readily available in nature, such as silk, cellulose, etc.[W1] Artificial polymer is commonly used synonymously with the term plastic. The plastics we meet in daily life are polymers. Polymers are classified in terms of molecular structure, chemical family, the shape of chains, mechanical and thermal behavior.[AK] The micro-structure of a polymer is related to the shape and architecture of the chains. The architecture of the polymer chains influences most of the physical properties of the polymer.[W1] The chains forming the polymers may be in the form of a straight, branched or interconnected network. In the classification made by considering the mechanical and thermal properties of the polymers, they are divided into three different groups. These are thermoplastics, thermosets and elastomers.[AK]

Generally, their backbone is formed from carbon atoms. If the main backbone of a polymer consisting of carbon atoms, it is called an organic polymer.[AK] The properties of the polymer depend on the properties of the atoms forming it. Polymers containing flor have high resistance to environmental influences. The polymers that contain flor atoms are called fluoropolymers. PTFE, ETFE, PVDF, FEP are fluoropolymers used in the membrane structures. A PTFE monomer molecule is shown in figure 2.3.a. Two carbon atoms (C) share an electron with four flor (F) atoms to form PTFE monomer. Polymers formed by combining two or more monomers are called copolymer. ETFE is a copolymer. The figure 2.3.b represents its chemical notation.



(a) Tetrafluoroethylene (PTFE - Teflon)

(b) Etylene Tetrafluoroetylene (ETFE)

Figure 2.3 Chemical representation of polymers

3.1.1 Classification of polymers

(a) Amorphous *(b) Semi crystalline* *(c) No crystalline Strongly cross-linked* *(d) Semi-crystalline Weakly cross-linked*

Figure 2.4 Type of polymer chains (Redrawn based on the source [M1])

• Thermoplastics

It consists of long molecular chains. The chains may be branched or unbranched. The chains are entangled, but there is no physical connection between the chains. Van der Waals forces hold the chains together.[AK] Their basic characteristic is that when they are exposed to heat, they become melted. Thermoplastics can be reused when after melted. They are shaped by heat and sensitive to temperature. They lose their mechanical properties over a certain temperature. The materials used in membrane structures are generally thermoplastic.

• Elastomers

It consists of long molecular chains with light cross-links. The geometry of chains may be a helical or zig-zag shape. Elastic deformation can exceed 200% under tensile load. When a load is applied to the chains its shape get straightened, when the load disappears the chains get its first shape again.[AK] They soften when heated but do not melt.[B2] The silicone rubber used as a coating material on the glass membrane is an elastomer.

• Thermosets

Its polymer chains are in the form of three-dimensional networks connected to each other by rigid cross-links. The chains shape may be straight or branched. It is stronger than thermoplastic but fragile.[AK] They cannot soften when heated, they burn at a high temperature.[LY] They have high resistance to heat. Its production techniques are different and recycling is difficult. Epoxy is an example to the thermosets.

3.1.2 Structure of polymers

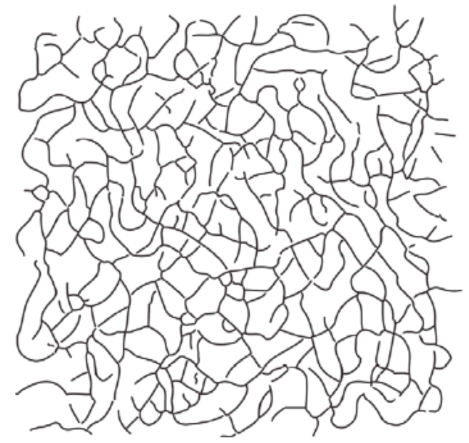
The distribution of atoms in a metal mass, exhibit homogeneous spread. The atoms are found with the same symmetry at every point of that mass. Because of this symmetry, the internal structure of the material does not change according to the directions. This kind of material is called isotropic. Polymers are not a homogeneous material. The distribution of molecular chains does not show a geometric order and symmetry. However, this does not prevent the polymers from acting isotropic. The statistical distribution of polymer chains provides same response in all directions.

Polymer chains are in two different order in a thermoplastic material. These are amorphous and crystalline. The structure in which the molecular chains are randomly distributed is called the amorphous structure. Molecular chains are intertwined in an amorphous structure. The structure in which the molecule chains are distributed in an order and symmetry is called crystalline structure. The chains are parallel to each other in the crystalline structure. Thermoplastics usually consist of crystalline and amorphous regions.[B2] The polymers which are made up crystalline and amorphous structures are called semi-crystalline. A polymer does not consist entirely of the crystalline area.[AK] The amorphous and crystalline area distribution rate varies between 10-80%. For example, PTFE consists of 40-60% crystalline region.[W2] Elastomers are completely amorphous and do not contain crystalline region.[B2] The thermoplastic materials used in the membrane structures are semi-crystalline.

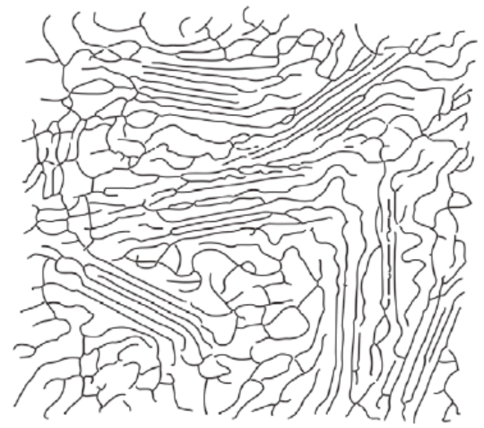
Amorphous and crystalline area distribution rate influences material's mechanical, chemical, optical and thermal properties. As the crystallinity of thermoplastics increases, the density increases and the volume decreases. If the crystalline areas are large enough, the light transmission of the material increases due to the light scattering.[AK] The material becomes more brittle and hard as the crystalline areas increase, more flexible as the amorphous areas increase.[W2]

There are van der Waals interactions among the molecule chains forming thermoplastic. The power of this interaction depends on the distance between the chains.[W2] The van der Waals interaction in the crystalline area is higher because the chains close together there.

The crystalline and amorphous structures show different reactions to the load and heat. When a tensile force is applied to the thermoplastic material, the chains in the amorphous area first react.[B2], [AK] Amorphous areas, when faced with the heat firstly soften, but do not show a sudden melting. Crystalline areas, when faced with heat, show a sudden melting at a certain temperature.[W3]



(a) Amorphous structure



(b) Semi-crystalline structure

Figure 2.5 Micro-structure of polymers (Source [B2])

3.1.3 Thermoplastics

During the production phase, if a tensile load is applied to the thermoplastic material, the entangled polymer chains open and straighten. At the end of this process, the crystalline regions get a position in the direction of the applied load. This process is especially performed to improve the mechanical properties of the fibers.[AK], [LY] The tenacity of the polyester (PET) yarn depends on the position and crystallinity of the molecular chains. After cooling, by stretching the filament, the crystalline region is positioned in the direction of the filament axis. As the result of this operation, the strength of the filaments increases in the direction of the applied tensile load axis, and the other axis falls. The mechanical property of the fibres in one direction, obtained by the deformation of the polymer chains, exceeds most metals and ceramic materials.[AK]

The mechanical behavior of thermoplastics varies depending on the temperature. When the temperature increases the molecule chains move more easily. When the temperature fall, the material solidifies becoming brittle. The temperature at which thermoplastics lose their flexibility and becomes brittle is called glass transition temperature (Tg). This temperature may be below or above room temperature, depending on the structure of the material.[B2], [AK], [LY] As the temperature increase, the free chains start to rotate and bend.[AK] The bond between the polymer chains in the amorphous structure is weak, above the glass transition temperature. At this temperature, the molecular chains in the crystalline region are not affected. If a polymer will be used as a solid, the ambient temperature should be lower than the glass transition temperature. The temperature which applied to the material at the glass transition temperature level if continues to increase, the material becomes fluid at a certain temperature point. This point is the melting temperature of the material (Tm). At this temperature level, the crystalline regions in the material are affected.[B2] At this level, the strength of the material is almost zero and the material is ready for molding and shaping.[AK] This temperature (Tm) must be exceeded in order to be welded a thermoplastic material. Elastomers do not melt because they do not contain a crystalline area, so they cannot be welded by melting process.[B2]

PVC is used as a coating material on a polyester weave surface. The glass transition temperature of PVC is about 100C. PVC is brittle under this temperature. One of the basic properties of a membrane material is its flexibility. For this reason, the pure PVC cannot be used as coating material. Plasticizers are added to reduce the glass transition temperature of PVC. When 40% plasticizer is added the temperature (tg) drops to -20 °C.[B2] As the percent of plasticizer in the PVC increased, the glass transition temperature of PVC decreases. The plastic products which containing plasticizers show improved durability and flexibility. The plasticizers added to the PVC don’t do a bond with polymer chains, they are settle between molecule chains.[W3] Plasticizers tend to leave PVC. As the plasticizers in PVC lost, the PVC becomes more brittle.[B2]

Some of the plasticizers added to PVC which used as a coating material on the base polyester weave are as follows.
Phosphates: It is often used to provide non-flammability property. Phosphates tend to leave PVC at high levels. Bacteria and mold can feed on by this plasticizer. This can lead to spread of mold and bacteria on the membrane surface.
Phthalates: The most widely used plasticizer due to its high compatibility with PVC. This plasticizer tends to leave PVC like Phosphates.
Chlorinated paraffin: Provides a high level of non-flammability. It tends to leave PVC at a high level. It also causes the surface to look dirty.[B2]

3.1.4 Mechanical behavior of thermoplastics

• Elastic behavior

Elastic behavior in a thermoplastics occurs as the result of two mechanisms. When a load is applied to the material, the covalent bond between the molecules elongates elastically. When the load is removed, the material automatically returns to its original size. This process is similar with metal and ceramics. Due to the applied load, there may be a deformation on the entire polymer chain. In this case, it may take a time that to return of the material to its initial shape when the load is lost, this may be hours may be months.[AK] The return of the material to its original geometry depending on the time is called nonlinear visco-elastic behavior. At this stage, we cannot see a permanent change in the shape of the molecule chains which forming the material, because the material is still acting as an elastic.

• Plastic behavior

When a tensile load applied to a thermoplastics exceeded a certain limit, the plastic deformation begins. This limit depends on the time, the ambient temperature, and the speed of the applied force. The chains in the amorphous structure forming the thermoplastics are entangled. With the increasing load, these chains are straightened, and they begin to slide on each other. In this stage, rotation, shear, stretching, untangle in polymer chains are the cause of permanent deformation.[AK]

When the crystalline region of polymer is exposed to the tensile load, it rotates in accordance with the load direction firstly. If the load continues to apply, the crystalline area is separated into small pieces. So, the crystalline regions slide over each other, polymer chains dissolve or break apart.[AK]

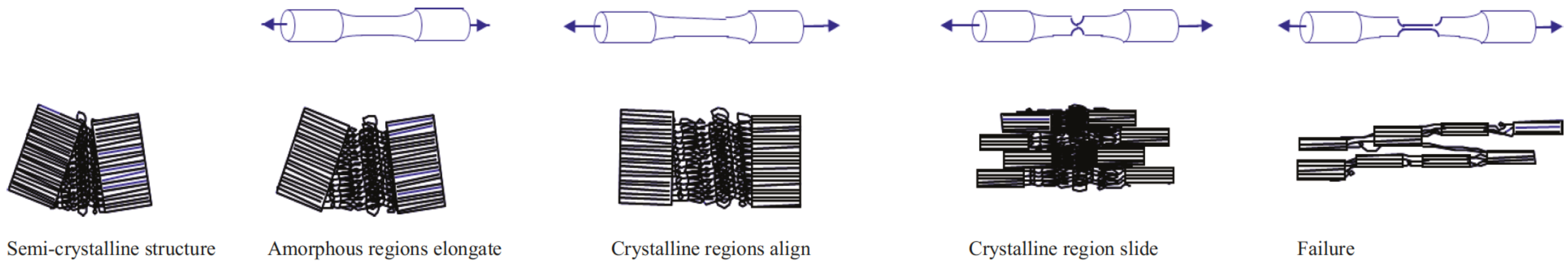


Figure 2.6 Illustration of the behavior of a semi-crystalline polymer under tensile load (The figure arranged based on the source [WL])

4. Membranes

The materials used in the tensile membrane structures can be examined in two groups.

a) Textile membranes: It is a composite material consisting of a textile weave that acts as a load bearing element and a coating layer as a protective.
b) Film membranes: It is a plastic material that is made up of a single layer.

In order to use a material as a structural membrane, it is expected that it first has the following properties.
Strength: It must carry tensile load coming from snow and wind loads, within acceptable deformation limits
Weldability: Suitability for strong joining method that can transmit tensile load
Durability: Resistance to chemicals (acids ...), biological (fungi ...), physical (UV ...), mechanical (creep ...) effects
Flexibility: It will not be damaged during manufacturing, transportation, installation process
Safety: Flameproofing capability in accordance with relevant standards

4.1 Textile membranes

Textile membranes are produced by assembling materials with very different technical characteristics. The most basic feature of a membrane is the tensile strength. Compared to films, the tensile strength of textile membranes is higher. The maximum breaking strength can only be achieved by weave yarns with superior mechanical properties.

The Membranes used for tensile structures with an anticlastic or synclastic surface are generally woven textile material.
In the broadest sense, the materials that are formed by the fibers are referred to as textile. Textile can be made from many materials. These materials come from four main sources. These are animals: wool, silk ...; plants: cotton, linen ...; minerals: glass fiber, asbestos ...; artificial fibers: polyester, nylon ...[WT] Technical textiles are materials that are produced for non-aesthetic purposes, their primary purpose is functionality. Technical textiles are divided into different categories according to the usage purpose. The classification system developed by Techtextil, Messe Frankfurt Exhibition GmbH covers 12 different application areas. In this classification, the textiles in the building sector are evaluated under the heading "Buildtech". The textile materials used in membrane structures are included in this scope.[WX]

There are two types of textile membranes that are commonly used. (From now it will be expressed as the membrane.)
a) PVC coating on the polyester base fabric (PVC/PES)
b) PTFE (Teflon) coating on the glass fibre base fabric (PTFE/Glass)

4.1.1 PVC/PES

The usage of PVC/PES membranes is more common than PTFE/Glass membranes.[DG] This is because of the price performance relation. PVC coating is applied to the fabric which produced using polyester (PET) yarns. Both materials are not protected against environmental influences. This protection is provided by the last lacquering layer on PVC. The applied final coat is usually PVDF for PVC.

It is a flexible material. Because of this feature, it gives advantages in terms of manufacturing and installing. It can be used in all type membrane structure that is temporary, permanent or foldable. The service life is between 15 and 20 years depending on environmental conditions and material properties.[DG] Light transmittance varies between 5-15%.[HT] The amount of elongation at break stage is 20-30%.[M5] Thanks to additives added to PVC, flame does not spread on the membrane surface. PVC extinguishes automatically when the flame moves away. PVC/PES membrane has B1 non-flammability property according to DIN 4102 standard. Creeps behavior starts around 70°C temperature, welds opens at 100°C. The material (polyester and PVC) melts at 250°C.[DG] Generally, it is produced in white color. Its recycle is possible.

The classification list created by Messe Frankfurt and the French Design Guide for PVC/PES membranes was shown in table 2.1. Membranes are produced in five different types. The classification is prepared according to the tensile strength. This classification does not contain information about the resistance property of the membrane to the environmental effects. The type of membrane to be used in a project is determined according to the maximum stresses that coming from structural analysis.

Membrane Type	Type 1	Type 2	Type 3	Type 4	Type 5
Surface Weight(g/m²)					
FDG	720	1000	1200	1400	2000
WG MF	800	900	1050	1300	1450
Yarn linear density (dtex)					
FDG	-	-	-	-	-
WG MF	1100	1100	1670	1670	2200
Tensile Strength warp/weft (kN/m)					
FDG	60/60	84/80	110/104	120/130	160/170
WG MF	60/60	88/79	115/102	149/128	196/166
Trapezoidal test warp/weft (N)					
FDG	-	-	-	-	-
WG MF	310/350	520/580	800/950	1100/1400	1600/1800
Yarn number per cm warp/weft					
FDG	-	-	-	-	-
WG MF	9/9	12/12	10.5/10.5	14/14	14/14

Table 2.1. Classification of PVC/PES membrane (Source: [DG])

(FDG) French Design Guide, (WG MF) Messe Frankfurt

The values shown in table 2.1 are;

- these values are determined according to short-term tests. The breaking strength of a membrane in the long term tests is lower.[PR]

- these values are determined according to uniaxial tests. Membranes have lower breaking strengths in biaxial tests.[PR]

- these values are the characteristic breaking value for 23°C temperature. PVC/PES membranes have lower strength when the temperature rises.

4.1.2 PTFE/Glass

It is obtained by PTFE (Teflon) coating on the fabric which weaved with glass filaments. It is covered with FEP as the top layer. Naturally, PTFE and glass filaments are flexible, but due to the high temperature applied during the PTFE coating process, the PTFE/Glass membrane becomes fragile and rigid. It is generally used in permanent structures. It is not suitable for temporary or foldable structures.

It is sensitive to folding. Its manufacture, transport and installation process requires special attention. In case of a hard folding, the PTFE coating gets damaged. This causes, to lose the strength of glass filaments by being exposed to water. Also, if it folded hardly, the yarns in the weave may break. Its light transmittance is 8-20%.[HT] If the PTFE coating is applied by laminating method, the light transmittance raises up to 50%.[B2] It requires higher pretension when compared to PVC/PES membranes. Its shear strength is higher than the PVC/PES membranes.[BR] Therefore, its form possibility is limited.

It has high-level self-cleaning capability. Its economic lifespan is longer than the PVC/PES membrane. Its cost is higher than the PVC/PES membranes.
The colorizing of the PTFE/Glass membrane is difficult, the colors are affected by the high temperature applied during the coating process.[ML] It can be colored, but it is not in RAL code.[HT] Due to the PTFE coating, it shows high resistance to environmental impacts. Its recycling is problematic.[B2] PTFE/Glass membrane has B1/A2 non-flammability property according to DIN 4102 standard. When the temperature rises up to 1000 degrees, the weave remains unburned. In case of fire, the welds of PTFE panels are opened around 250°C.[DG]

It can be used in all climatic conditions. Shows less creep behavior than PVC/PES membranes. Its modulus of elasticity is higher than PVC/PES membranes.

Type	G1	G2	G3	G4	G5	G6	G7
Tensile strength warp/weft (kN/m)	26/22	43/28	70/70	90/72	124/100	140/120	170/158
Filament diameter (micron)	9	6	3	6	3	3 or 6	3
Surface weight (g/m²)	500	420	800	1000	1200	1500	1600
Trapezoidal tear warp/weft (N)			300/300	300/300	400/400	500/500	450/450

Table 2.2 Classification of PTFE coated glass membranes (Source [DG])

Corresponds to the PTFE/Glass G3-G7, PVC/PES 1-5 types.

4.1.3 Other important membrane materials

4.1.3.1 Silicon/Glass

It has the same mechanical properties with PTFE/Glass membrane. The reason for the difference between them is the coating materials.
It is a rarely used membrane. Its surface is charging with static electric and collect the dust. It is a fireproof material.[M5] It is a flexible membrane. It can remain flexible at -50 + 200°C.[PR] It cannot be welded thermally. This is because the silicone used as the coating material is an Elastomer.[B2] It adheres well to the glass weave. Provides high protection against UV rays and atmospheric effects. Silicone rubber protects the glass better than PTFE from water and moisture. Despite its many advantages, its use is limited due to the problem of surface cleaning and weldability.[DG] Its light transmission is around 25-30%.[HT]

4.1.3.2 PTFE (coated or uncoated)

The yarns to be used in the weaving are scraped from the block PTFE material. It is resistant to abrasion, and heat. It is fireproof and UV resistant. Its tensile strength is 160N/mm².[B2] There is two version of the fabric, as the coated and uncoated. The uncoated version is not waterproof. The coated version is produced by PTFE coating on PTFE fabric. The basic feature of PTFE fabric is that it is extremely flexible and does not break. The light transmittance is 40%. It has a high resistance to environmental impacts.[HT] If there is no limitation in the budget, especially the uncoated version is preferred in foldable structures. This is because of its high light permeability, extreme flexibility, and long-term durability.[BC] Its joining method is seaming.

4.1.3.3 Aramid (Kevlar)

Aramid is a polymer. It is five times stronger than steel. It provides lightness and strength together. It is more flexible than glass filament.[WP] Its breaking strength is 24.500N/5cm, the breaking extension is 5-6%. Aramid membranes are the strongest synthetic fabrics. It is resistant to chemical and thermal effects. Its UV resistance is low. For this reason, it needs to be coated with opaque PVC or PTFE. It can be used in applications where very high strength is required and light transmittance is not required.[M5] One of its applications is pneumatic beams structures (air-beam) which requires high air pressure.[HT]

4.1.4 Weave

The membrane materials used in the anticlastic membrane structure are woven textile materials. A weave is consisting of two sets of yarn that perpendicular to each other. The loads acting on the membrane surface are borne by the yarns that forming the weave. The direction of the yarns is taken into consideration in the design process of membrane structures. The breaking strength of a membrane depends on the mechanical properties of the yarn forming the weave. The placement of yarns in the fabric is symmetrical. Two types weaving techniques are used in the manufacturing of membranes. These are plane 1/1 and panama 2/2, 3/3. The plane weaving is produced from single yarn and panama weaving is produced from two or more yarns.

In the weaving process, the yarns settled in the direction of the loom are called warp yarn. The warp yarns are lined side by side on the weaving machine, under constant tension. These yarns are in two rows that can move vertically with a certain angle. The yarn that is 90 degrees perpendicular to warp yarns is called weft yarn. The weft yarns passing between the warp yarns moves from one end to the other along the width of the fabric. When this process is complete, two rows of warp yarns change its angle. At the end of these two basic movements, a line of weaving occurs. In the weaving process, both yarns lose their linearity and they become curved. The weft yarn curvature is greater. The curvature of the yarns affects the mechanical properties of fabrics.

There is no other bond between warp and weft yarns such as a knot or a loop, except physical contact. There is friction between the yarns due to the curvature that result of weaving process. This friction between the yarns keeps the weave together. The curvature, tension, and frequency of the yarns determines the mechanical properties of weaving.

The unit geometry of the yarn curvature that is formed as a result of each sub-upper process of weaving is called “crimp”. Due to the crimp geometry of the yarn, the tension in one direction affects the geometry of the yarn in the other direction. When a force applied to the weave, which higher in a direction, the yarns become more straight in that direction, in other direction more curved. The reciprocal change of the yarns curvature, which occurs depending on the direction of the applied load, is called "crimp interchange". It is one of the most important factors determining mechanical behavior of membranes. There are two important geometric results of the curving the yarn while forming the weave.

• **The yarns are curved (two dimensional) in both directions;** This curvature is not the same in both directions. Warp yarns are more linear because they are under a constant tension. Weft yarns are more curved due to low tension. When a tensile load applied to the membrane surface, the yarns cannot carry the load on own axis because of this curvature. Membrane shows less ductile behavior when a load applied at the warp direction. Because warp yarns are more linear, they meet the load with less elongation. This difference in the weave geometry is one of the basic factors affecting the mechanical behavior of the membranes.

• **The final weave surface is three dimensional;** Surface geometry is important in terms of bonding of the coating to the base fabric. That bond between weaving and coating is effective on the weld strength capacity of the membrane. The stress in the membrane weld is the shear stress. The shear strength of the weld increases depending on the crimp height. The crimp depth is not the same in both direction. So, the weld load carrying capacity of membrane changes due to the direction.

4.1.5 Yarn

Tensile strength of a membrane depends on primarily the mechanical properties of the yarns. The weave yarns used in membrane materials are generally glass and polyester. The reason for the use of these materials is their relatively high tensile strength and low elongation under the loads.

A weave yarn are consist of filaments. Filaments are obtained by extruding the melted raw material. The thickness of the filaments varies between 3-25 microns. A single filament is not an easily processable material. Filaments assembled together are transformed into yarns by rotating them on their axes. This process is called " yarn spinning". The amount of rotation of the yarn on its axis affects the mechanical properties of the yarn. The tensile strength of the yarn increases with the spinning process. Some of the filaments forming yarn may be broke or have lower elasticity. In this case, these filaments transmit less load or cannot transmit any load. When filaments rotate on its own axis, the entire filaments can carry load. This is possible because of friction.[B2] Because of spinning, the friction between the yarns increases, so the dimensional stability of the fabric also increases. The cross-sections of the filaments vary, some are weaker than others. If the filament bundle has spun, the axial loads cause to increase of friction between of the filaments. This prevents the breakage of weak filaments and provides more effective load sharing.[BR]

Membranes are produced in different types according to tensile strength. As the total amount of yarn used in a membrane increases, the tensile capacity of the membrane also increases. In order to increase the tensile strength of the membrane, the number of warp and weft yarn used in a sequence of weaving is increased. For this reason, in the production of a membrane with high tensile strength, panama weaving technique is used. At this point, the following question is important. Why is the number of yarns increased instead of to increase the cross-section of the yarns?

A yarn reaches maximum tensile strength capacity when the load applied on its axis. The yarns in the weave are curved, so they do not carry the load in its axis. The load carrying capacity of the yarn decreases as the amount of crimp increases. This is because the high contact force causes the loss of strength. Increasing the cross section of the yarn causes the crimp to increase, thus increasing the contact force. At this point, the strength of the yarn and the welding capacity of the membrane are against each other. It is required that low crimp for high yarn strength, high crimp for high welding strength. The solution is provided by increasing the number of yarns.[B2]

The amount of yarn used in the membrane is expressed as dTex in the manufacturer presentation documents. (dTex is the expression of 9000m yarn in grams.[DG]) For a 900gr/m^2 membrane, the total polyester yarn weight specified by a manufacturer is 288gr. The rest part coming from coating materials. For an example, the characteristics of the yarn used in the weaving of a membrane can be explained as follows.

F 200 Z60: The yarn consists of 200 filaments. Each meter of the yarn is rotated 60 times in the direction Z (right side).[HT]
1100 dTex: 9000m of the polyester yarn used in weave is 1100gr.
12x12 Panama: There are 12 yarns in both directions, in the 1cm fabric.

4.1.5.1 Polyester yarn

Polyester is the name of a general product group.
Membrane manufacturers use the abbreviation PES for polyester. However, in material science, this abbreviation is the technical name of another material (polyethersulphone).[KN] The raw material of polyester yarns used in the membrane structures is PET (polyethylene terephthalate). The drink containers used in daily life are also produced from this material.

Polyester is a thermoplastic. It is semi-crystalline material. It has amorphous and crystal region. Polyester yarn is produced from PET filaments extruded at 265°C.[B2] Its resistance to UV light is weak. A polyester weave exposed to UV rays loses 50% of its strength in two years.[ML] For this reason, the weave must be coated.

The polyester yarns used in the tensile membrane structures have high tenacity. Tenacity depends on crystallization degree and orientation of polymer chains. After the cooling process, polymer chains are stretched and its orientation is increased. This process allows the elevation of the tenacity and the elastic module. The tensile strength of high tenacity polyesters is at least 1000N/mm², the elasticity module is 15000N/mm².[B2] Glass transition temperature of PET polymer is 75°C, crystallization is 130°C, melting temperature is about 260°C.[WP]

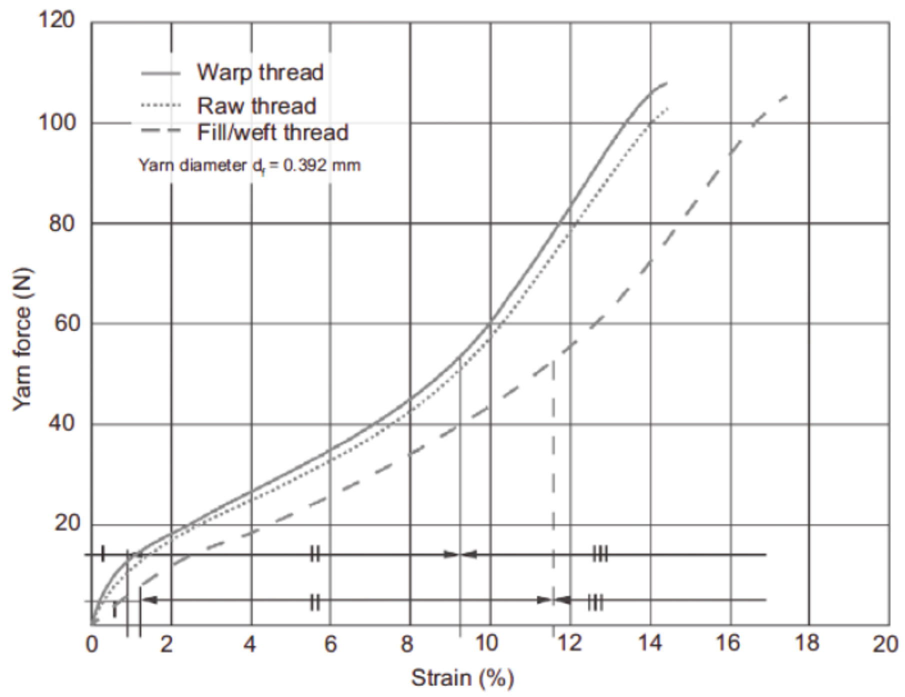


Figure 2.7 Force-strain path of a polyester yarns
Source [B2]

The stress-strain diagram of polyester filaments consists of three characteristic zones. (Figure 2.7)
Zone 1: The zig-zag structure of polymer chains is opened. Chains become more straight. **Zone 2:** The chains in the amorf region begin to straighten. **Zone 3:** By straightening of the jammed chains in crystalline fields are formed. This result increases the stiffness.[B2] Figure 2.7 represents the elasticity of the yarns increases after 9% elongation.

The table 2.1 shows the breaking strength of the PVC/PES membrane in warp and weft direction. Even though the same yarn is used in both direction of the weave, the breaking strength of the membrane in the weft direction is lower. This is due to the fact that the weave is exposed to high temperature during the coating process. The coating temperature is above the glass transition temperature of the polyester.[DG] The temperature during the coating process is about 120-180°C. This temperature causes repositioning of the polymer chains forming the yarns.[UH] This phenomenon is called the "weft jump". The yarns in warp direction are not affected by this phenomenon because they are under a certain tension. However, the weft yarns are under less tension, they shrink due to heat.[DG] This causes the weft threads to have a low breaking strength and the breaking point elongation is higher. There is a different weaving method in which the yarns in both directions are kept under equal constant stress.

Water and moisture carry some harmful substances to the weave. Bacteria and mildew occur in the yarn due to moisture. They appear in brown-yellow lines. This result is called “wicking”.[DG] If polyester threads are not adequately protected against water, wicking occurs in the weave. The yarns are chemically treated to prevent water progressing through the filaments before the weaving process. The yarn subject to this process is called “low-wick” yarns. The yarns used in the membrane materials have “low-wick” property.

4.1.5.2 Glass yarn

The glass is an inorganic material. There is no specific melting temperature. It is molten at 2000°C, it starts to change at this temperature. Different types of glass filaments are produced, such as E-glass, C-Glass, S-glass.[WP] E-glass filaments are used in the tensile membrane structure. The production of filaments is carried out in diameters of 3,6,9,11 microns. The strength of the filament depends on its diameter.[DG] In the membrane structure, 3 micron thick filaments are used. This diameter provides good flexibility and strength for membrane materials. The tear strength is higher than steel which is the same thickness although its weight is less.[HT] It is sensitive to moisture. If it is exposed to moisture it will lose its strength. It is a disadvantage that they are fragile and vulnerable to abrasion. It is strong against UV rays. It is a non-flammable material. The fabric is covered with PTFE or silicone. The silicone coating is rarely applied.

The stress-strain graph of the glass yarns is linear until the break. Tensile strength is 3500 N/mm^2, the elastic module is 70000 N/mm^2.[DG] It shows very little creep behavior compared to other filaments. It is amorphous and therefore isotropic, its mechanical behavior is the same in both directions of the filament.[KN] Its elongation at break stage is 4%.[WP]

4.1.6 Coating

Textile membranes are composite materials consist of multiple layers. It is the weave that determines the load bearing capacity of the membrane. A woven fabric is not protected against environmental influences without coating layer. Polyester loses its strength when exposed to UV rays, glass moisture, and water. The surface of the base fabric must be coated to protect against external influences. The main factor determining the lifespan of the membrane is its resistance to environmental effects. The resistance of the membrane material to chemical, biological, physical, mechanical effects is provided by coating material.

Coating provides weldability to the material, stability to the woven geometry, shear strength, water resistant, flame retardancy (for polyester).[B2] PVC and PTFE are generally used as coating material. Coating process is applied by different techniques according to the chemical properties of these materials. During the coating process, the weave is exposed to high heat. For this reason, coating process influences mechanical properties of membrane. Coating is indicated in g/m^2 as a characteristic in membrane specification documents.

4.1.6.1 PVC coating

PVC coating is usually used on the polyester weave.
The molten coating material is spread on the polyester weave by the "coating knife" method. Before the coating process, a special primer layer (isocyanates) is applied to the woven surface to strengthen the bond between fabric and coating. Coating material does not consist of pure PVC. In order to improve the properties of the membrane, additives are added to the coating material. Additives and plasticizers are added to the pure PVC, providing flame retardancy, UV resistance and flexibility.[B2] When the flame moves away, the material self-extinguishes. Due to this feature, the melt PVC particles quickly extinguish and do not cause flame spreading. Plasticizers ensure that PVC remains flexible at low temperatures. PVC becomes fragile due to plasticizers leave from PVC over time. This is one of the important factors determining the lifespan of PVC/PES membranes. If a membrane surface does not have sufficient prestress, it will fluctuate in light wind. This fluctuation reduces the service life of membrane. This fluctuation has a more negative effect on a PVC/PES membrane at low temperatures. The reason for this is that PVC becomes more brittle at lower temperatures.

In order to increase the resistance of PVC coating to environmental effects, final coat is applied. The top coat material applied on PVC is usually PVDF. PVDF is a thermoplastic from the fluoropolymer family. PVDF has excellent resistance to UV rays. It protects membrane against environmental influences. Membrane surface remains clean because of PVDF top coat. Topcoat serves as a barrier to prevent plasticizer leaving from PVC. It extends service life of PVC.[B2] Prevents the formation of micro-cracks in PVC coating.[HT] Its application thickness is 5-10 microns.[SD] Acrylic is a different alternative for the top coat. Its UV resistance is not as good as PVDF.[HT] The lifespan of acrylic coated membrane is shorter than PVDF coated.

Amount of light transmittance is controlled by coating and it is also produced as a light-proof (black-out). It is possible to give the desired color to the coating. The standard production color of membranes is white. If requested above a certain amount, it can be prepared in desired color, by its manufacturer.

4.1.6.2 PTFE coating

PTFE (Teflon) coating is made on the weave consisting of glass yarns. PTFE is a thermoplastic from the Fluoropolymer family. PTFE doesn't really melt. For this reason, the coating cannot be applied with the knife method. It is applied by the immersion coating method on the glass weave. In this method, the glass weave passes through an emulsion in which PTFE pieces are found. Some particles stick to the surface of the weave. This process is repeated until the required thickness is reached. PTFE coated glass weave is sintered between 350-380°C temperature. PTFE can only be coated on a material that can withstand high temperatures. PTFE coating acts as more or less ceramic.[B2]

PTFE has superior properties not found in other polymers. It can be used at -200 +260°C temperature. For this reason, it is suitable for all climatic conditions. A change in temperature does not affect its economic lifespan. It maintains flexibility at very low temperatures. It doesn't require a plasticizer to achieve this. PTFE is an incombustible material. Its surface energy is one of the lowest materials. It has a nonstick surface, so the surface does not get dirty. It cleans itself with rainwater. It provides high protection against water for glass weave. It has high resistance against UV rays. It does not show signs of aging due to UV rays.[DG] Its final coat is FEP. FEP is a thermoplastic from the fluoropolymer family. FEP layer increases impermeability, weldability, and resistance to bacteria.[HT]

Another coating method is laminating. In this method, the PTFE layer is applied to glass weave under high temperature and pressure. The bond between the glass weave and PTFE coat is weak at the laminate method. If the membrane folds, this bond will be damaged. PTFE is exposed to high heat during coating. For this reason, the surface color is light brown. Its surface color gets white with time. This time is 1 to 6 months depending on the sun's rays intensity.[B2]

4.1.6.3 Coating and weld

A membrane structure surface is formed by the joining of several membrane panels. One of the basic requirements for the use of a membrane in manufacturing is that it must suitable for the joining method which will transmit the stresses. Polyester or glass weave that carrying a load, can transfer the load by means of the coating layer. The weave cannot be welded directly to each other. Molecular properties of coating material determine the type of welding. PVC and PTFE are thermoplastic materials. PVC is more suitable for welding due to its low melting temperature.

The best weld for PVC coating is obtained with a high-frequency welding machine. The reason for welding PVC with high frequency is the polarity property of this material.[B2] The molecules that are active in the high-frequency effect heat up and allow two surfaces to reach a homogeneously melt state. By applying a suitable pressure to the molten PVC surfaces, bonding is achieved between two surfaces. A PVC weld is more sensitive to temperature. The reason for this is the low melting temperature of PVC. As the ambient temperature increases, PVC welding strength decreases. PVDF coating on PVC surface may prevent welding due to high melting temperature. In this case, PVDF layer must be cleaned from the PVC surface before the welding process.

A PVC/PES membrane weld provides 90% of the tensile strength of the membrane at 23°C, and 50% at 70°C.[DG] Two pure PTFE cannot be welded directly to each other. PTFE weld is usually made using FEP tapes at the appropriate temperature and pressure. If the coating on the weave surface is laminated, the strength of the welding is lower.[B2] PTFE/Glass membrane welds are less affected by temperature.

Silicon is an elastomer, so its weld is only possible via the vulcanized method. A molecular bond is formed between two silicone surfaces through the appropriate film.[B2] Its welding process needs at a certain temperature and pressure.

4.1.7 Mechanical properties

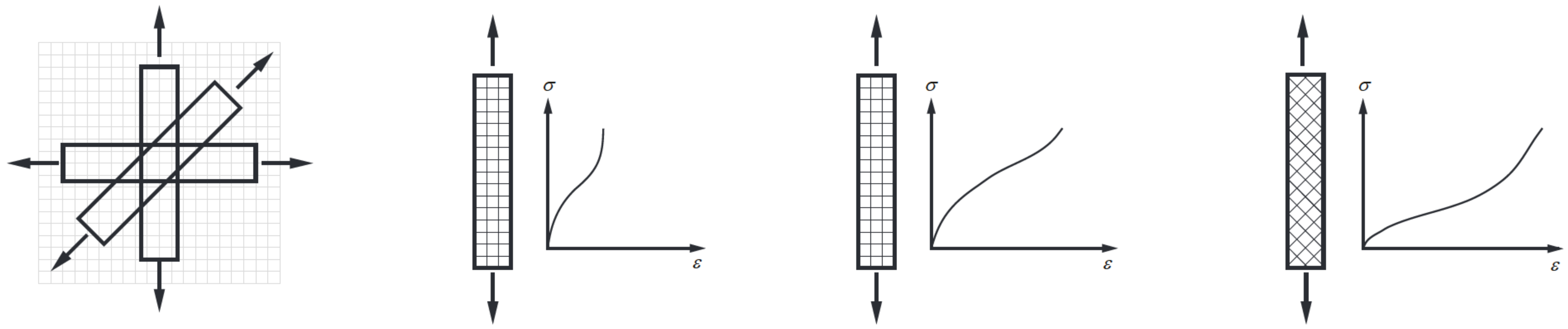
Mechanical behavior of the membranes is nonlinear, anisotropic and non-elastic.[B2]

4.1.7.1 Nonlinearity

Nonlinearity means that the stress and strain ratio is not constant. Stress is the amount of load applied to a material for per unit area. Strain indicates the amount of extension of the material under the load. The stress-strain ratio of a linear material is constant. This constant rate may be valid until to a certain point or material is up to break. For example, if a 1 cm^2 linear material was elongating 0.1 mm under 1kN load, it will elongate 0.2 mm under 2 kN load. When this relationship is shown graphically, it follows a straight path due to the constant ratio. The stress-strain graphs below show that the relationship between stress and strain is not linear.

4.1.7.2 Anisotropy

The relationship between stress and strain in an isotropic material is the same in all directions. A membrane is anisotropic, orthotropic material. For this reason, it shows different mechanical behavior according to the direction of the applied load. The main reason for this is that a membrane consists of weave. The weave is made up of two threads perpendicular to each other. The geometry of yarns in weave is different in both directions. Warp yarns are more straight because they are under a constant tension during the weaving process. For this reason, when force is applied to the membrane in the warp direction, the yarns meet the load with less elongation. (Figure 2.8.b) Weft yarns are more curved. When a load is applied, this direction shows more elongation due to curvature. (Figure 2.8.c) Another reason for the anisotropy in PVC/PES membranes is that weft yarns have lower elastic modulus.



(a) Membrane strip directions *(b) Warp direction anisotropy* *(c) Weft direction anisotropy* *(d) Diagonal anisotropy*

Figure 2.8 Membrane nonlinearity and anisotropy (Redrawn based on the source [B2])

4.1.7.3 Non-elasticity

If a tensile load applied to an elastic material by repeating within the elastic limits, the stress-strain graph follows the same path each time. In other words, the material loses the elongation which it received under load, and returns to its initial geometry. A deviation from this load path means that there is permanent deformation at the material. This mechanical behavior is completely different at the membrane materials. Although the same load is applied to the membrane twice, the graph is following a different load path. (Figure 2.9.c) There is no deformation in the micro-structure of the material. The material keeps its strength, but a permanent change is occurring in the yarn geometry. The reason for that is the change in the curved geometry of the yarn forming the weave. Therefore, the behavior of membrane changes depending on previously applied loads.

Visco-elasticity

The mechanical behavior of the membranes under the load change with time. This situation is explained by the phenomenon of "visco-elasticity". There are two basic mechanical results of this phenomenon.

• Creep

The elongation of a membrane under a constant tension load increases with time. The strain applied membrane during prestressing is not constant, it continues to increase. This phenomenon is one of the effects which describing the service life of the PVC/PES membranes.

• Relaxation

The tension of the membrane surface which is subjected to the constant stress decreases over time. This effect is taken into consideration when determining the amount of pretension applied to the membrane surface. Therefore, a PVC/PES membrane structure surface may need to be prestressed again.

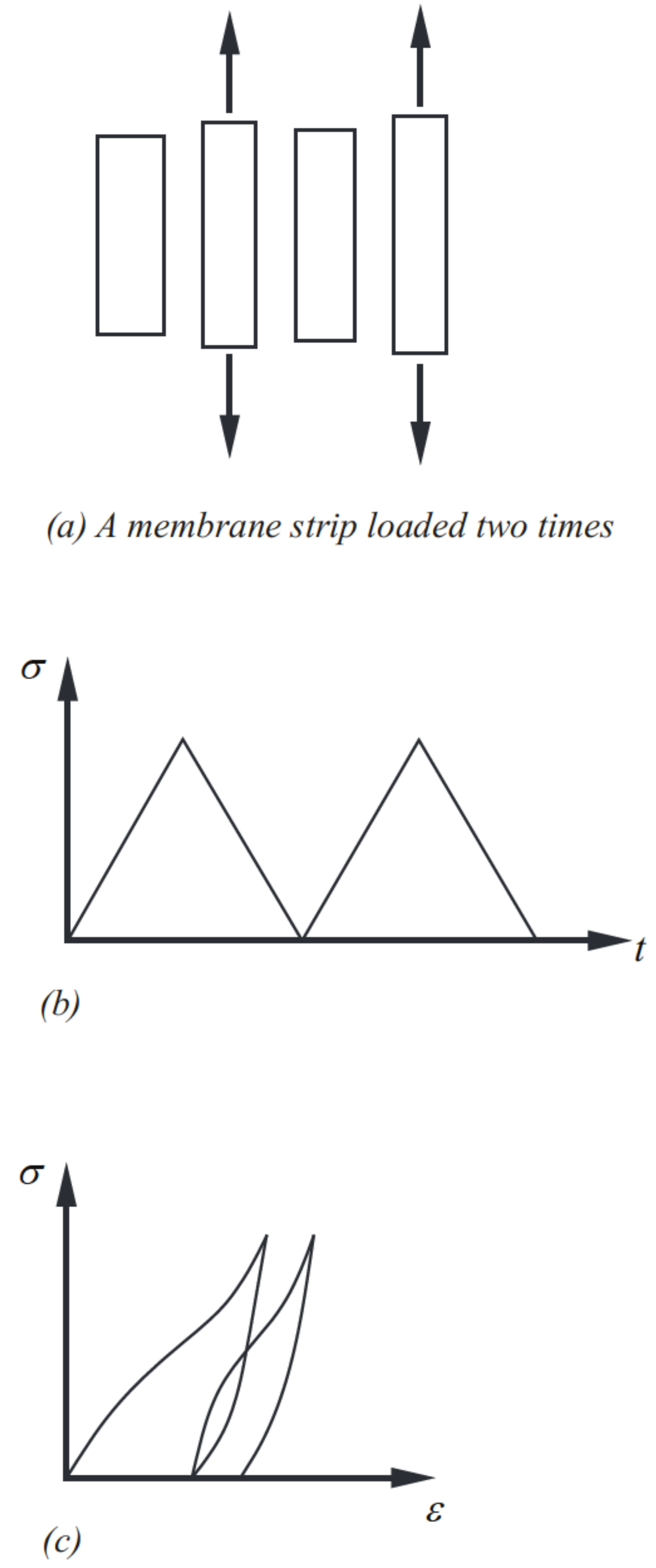


Figure 2.9
Membrane non-elasticity
(Redrawn based on the source [B2])

4.1.8 Test

In order to use a material as a structural element, it is necessary to know its behavior under the load first. Membranes exhibit more complex mechanical behavior compared to traditional building materials. The behavior of the membranes under load influences the design, analysis, fabrication, and assembly processes. Membranes bearing loads only as tensile, but this tensile behavior is not one directional. The elongation and breaking point values obtained from a tensile test in one direction do not provide the required knowledge for analysis and fabrication. Mechanical behavior of membranes is complicated because of the two directional nature of the weave and the reciprocal interaction of these directions. In addition, mechanical behavior of membranes changes due to temperature and time. In this context, all of the mechanical behavior of the membrane is not completely under control.

When performing the static analysis of a membrane structure, the membrane material is modeled as an orthotropic linear-elastic material.[UH] In reality, a membrane is not linear and elastic. An elasticity and Poisson ratio value are used for the structural modeling of a membrane structure. This is a simplification. Different tests are performed to determine the mechanical properties of the membrane materials. These tests are unaxial, biaxial, shear, welding, tear, and so on. The two basic tests required for analysis and manufacturing are plane biaxial and uniaxial tests.

4.1.8.1 Unaxial test

It is used to determine the behavior of a membrane and connection details under the load. A force is applied to the test sample prepared in the direction of warp and weft until to break. In this way, the ultimate tensile strength of the membrane and the amount of elongation at the break point are learned. The uniaxial test is intended for manufacturing. Membrane connection details show mechanical effects such as peeling, rupture, slip, tear, under the tensile load. These effects are investigated by the uniaxial test. During the test process, membrane weld, border cable pockets, aluminium channels, are exposed to axial load. In this way, the mechanical capacity of the detail and the possible causes of the failure are understood. The mechanical behavior of membrane and connection details, changes depending on the environment temperature and the speed of the load. In the tests, different scenarios are investigated taking into account this effects.
Membrane behavior varies depending on the time. Relaxation and creep behavior can be measured with these tests.[B1]

The sample width, length and applied load speed of the uniaxial test that prepared to learn the breaking strength of membrane are specified in relevant standards. According to the EN ISO 1421 test, the sample has a width of 50mm, a length of 200mm and a test speed of 100mm/min. The environment temperature for this test is 23°C.[PR] This test is called a short-term test.

The strength of a membrane under a constant permanent load decreases with time. To take this effect into account, the long-term tests are conducted. The aim is that along the lifespan of membrane, its tensile strength is within the safety limits. For this purpose, the long-term test procedure is applied to the test sample, which is usually exposed to a certain load for 1000 hours.[B1]

4.1.8.2 Biaxial test

There are three different types of biaxial testing. These are bursting test, cylinder test, and plane biaxial test. Biaxial plane testing is more suitable for textile membranes.[BR] Biaxial tests are not performed to measure strength. It is done to determine the compensations values and elastic modulus.[DG] The membranes exhibit complex behavior when the two directional load is applied. The main reason for this is the curved geometry of fabric. The curvature of the yarns reacts differently according to the load ratio in the directions.

a) Biaxial test for describing modulus of elasticity
Stresses formed on membrane surface are borne by the weave yarns forming membranes. These yarns are perpendicular to each other in two directions. During the biaxial test process, an axial load is applied to the membrane specimen in warp and weft direction, in different ratio. The loads to be applied to the membrane specimen are determined according to the highest stresses that coming from the structural analysis. Taking load combinations into consideration, the applied loading - unloading program to the membrane specimen is called “load history”.

• **Membrane stress-strain graph depends on the ratio of the load that applied to the warp and weft direction;** The tests for determining the elasticity modulus simulate the behavior of the structure under the real conditions. The real loads are snow and wind.[DG] The first stage of the loading program is the loads applied during the prestressing or installing phase. In the following stages, stresses due to snow and wind loads are applied. Depending on the form of the membrane surface and the direction of the loading, the stress distribution changes. The applied load during the test can exist in both directions, or it can be minimized in one direction while creating the highest peak in other direction.[B1] The load applied to the membrane specimen may be in the ratio of 1: 1, 1: 2, 2: 1.

• **Membrane stress-strain graph depends on the previous loading;** It is not enough to apply these loads once, because the strain does not turn to zero when the load disappears. As the load cycle amount increase, the stress-strain relation difference decreases and the mechanical behavior of the membrane becomes consistent.[BR] There is no common standard for how to perform a biaxial tests. Because of this, the number of the cycle depends on the practitioner. At the end of the biaxial test, the stress-strain graph for the membrane is obtained. The values obtained from the test are used to describe the elastic modulus. The test results are valid for that loading program.

b) Biaxial test for describing compensation values
It is a test for manufacturing of membrane surface. Compensation is the process of shortening the membrane surface to get the desired prestress on the membrane surface. When a load is applied to the shortened membrane at a certain amount, the membrane acquires the necessary prestress and the initial designed geometry. How much the membrane will be shortened depends on the mechanical properties of the membrane and the amount of the prestress to be applied. The compensation values are based on biaxial test result.

4.1.9 Membrane safety factors

In the structural analysis process, the safety factors used for membranes range from 5-10.[BR] There are different methods to define these coefficients. The A factor method is one of these methods. This method is based on the Ph.D. thesis of Jörg Minte and DIN 4134. Jörg Minte has done many experiments to determine these factors. According to the A factor method, the strength of membrane and connection details is reduced by the four different reasons. These factors are the biaxial strength, long-term load, degradation, and temperature.[DG] A membrane structure is not exposed to these effects in all load cases. Especially, the temperature reduction effect depends on the load combination. There is no need to use the temperature reducing effect in case of a stress caused by snow load.

(The following equation and values based on the source [DG])

Membrane allowable stress

$$f_d = \frac{f_{tk}}{\gamma_f \cdot \gamma_M \cdot A_i} = f_{tk} / A_{res} \quad \text{(Eq. 2.1)}$$

f_d = Allowable stress

f_{tk} = Tensile strength defined as 5% fractile of at least 5 strips 10cm wide, tested at 23°C (codes: DIN 53 354, ISO 1421)
(Alternatively, from Minte, 0.868 x mean tensile strength for the fabric or 0.802 x mean strength for / near the seams)

γ_f = Load factor

γ_M = Material safety coefficient for all approved materials: 1.4 within the fabric surface, or = 1.5 for connections

A_i = Combination of reduction factors depending on load case

Load factors

Permanent: γ_f = 1,5 x Prestress + Self Weight

Wind Storm: γ_f = 1,6 x Prestress + Self Weight + Wind Load

Maximum Snow: γ_f = 1,5 x Prestress + Self Weight + Snow Load

A Factors

(The values in the parenthesis is for connection details)

A_0	= 1.0 – 1.2 (1.2)	The breaking strength of the membrane is lower in the case of biaxial stress.[B2] The breaking strength value used for membranes comes from uniaxial tests. In fact, a membrane structure surface is under biaxial stress.
A_1	= 1.6 – 1.7 (1.5 – 3.4)	The strength of a membrane is reduced due to the ongoing permanent load. This decreasing strength is called "residual strength". The residual strength is lower than the strength obtained with the short-term test.[B2]
A_2	= 1.1 – 1.2 (1.2)	Environmental effects reduce the breaking strength of the membrane. These effects can be UV rays, biologic, chemical, mechanical.
A_3	= 1.1 – 1.25 (1.4 – 1.95)	When the temperature is getting high, the tensile strength of the material decreases. A reduction factor is valid if temperature and load occur at the same time. This effect is not taken into account in case of a stress caused by snow load.

Safety factors for material;

Permanent:	$A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3$	**= 4.9 - 6.4**
Wind storm:	$A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_2$	**= 2.9 - 3.2**
Maximum snow:	$A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_1 \cdot A_2$	**= 4.4 - 5.1**

Safety factors for connection; (only welded seams with appropriate widths for fabric type)

Permanent:	$A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3$	**= 6.7 - 9.5**
Wind storm:	$A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_2$	**= 3.5**
Maximum snow:	$A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_1 \cdot A_2$	**= 4.9**

4.2 Films (Foils)

Films are thermoplastics, composed of a single layer. Compared to textile membranes, its mechanical properties are not suitable for a wide span.
Structurally, the most used film is ETFE.[B2] ETFE films are generally used in pneumatic cushion construction. The surface gets prestress, by applying internal pressure to the cushion that consisting of two or more layers. A single layer ETFE is also used as a mechanically prestressed anticlastic membrane structure material. In such an application, ETFE surface must be reinforced with steel cables.

4.2.1 ETFE film

ETFE thermoplastic is a semi-crystalline material, its crystallinity is 50-60%.[SD] Its polymer structure is in form of long linear molecular chains. It consists of a combination of two different monomers. ETFE is defined according to the thickness (µm). It is produced in thickness between 50-350µm.[PR] 200µm ETFE has six times less tear strength compared to PVC/PES membrane. For this reason, the span that can be covered with ETFE material is shorter than the textile membranes. Estimated economic life is more than 25-30 years.[M5] The flexibility of ETFE depends on its thickness.[SD] The maximum allowed thickness is 250µm. This thickness is sufficient for a 5m span when considered the standard roof loads.[M6] It has high resistance to solvents, chemicals, UV rays. It has the feature of not holding dirt on the surface. The melting temperature is between 250-270°C. The weight is 1.73-1.77g / cm^3.[DG]

Thickness (microns)	**Weight** (g/m^2)	**Tensile strength** L/T (N/mm^2) (DIN 53455)	**Tensile strain** L/T (%)	**Tear strength** L/T (N)
50	87,5	64/56	450/500	450/450
80	140	58/54	500/600	450/550
100	175	58/57	550/600	430/440
150	262,5	58/57	600/650	450/430
200	350	52/52	600/600	430/430
250	437,5	>40/>40	>300/>300	>300/>300

Table 2.3 ETFE film properties (Source [DG])
L/T (Longitudinal/Transversal direction)

ETFE film is produced by extruding the polymer particles at a temperature of about 340°C. There are two different extrusion methods. These methods are the slit-die and the blown method. The properties of the ETFE vary according to the extrusion method. The thickness of the blown method is limited to 150µm. Its width is more. Its isotropy is less. In the slit-die method, the upper limit of thickness is 350µm.[PR] Flat extruded films are more advantageous in terms of light transmittance, gloss, crystallinity, stiffness, homogeneity, and consistency of thickness. Blown films are advantageous in terms of strength. The disadvantage of blown films is the risk of breakage if they are folded.[SD] The films produced by the slit-die method are used in architectural applications. The films produced by the blown method are generally used in the greenhouses.

The light transmittance of 200µm ETFE is roughly 95%.[M5] UV rays pass the ETFE. UV rays help plants grow and provide natural protection against bacteria. For this reason, ETFE is especially used in greenhouses, botanical gardens, swimming pools, and stadiums.[M4] Due to UV radiation transmittance, the first permanent ETFE roofs were applied in botanic gardens in the 1980's.[M3] It can be colored by adding pigments and it can be printed on.[M5] In this way, the light transmittance can be reduced. It is completely recyclable.

It has B1 class non-flammability property (DIN 4102). When the temperature reaches 275°C, ETFE dissolves and holes occurs on the surface, gas, and smoke come out from this hole. The melted ETFE particles quickly cool down and fall to the ground without burn.[M4] Its weld is done by thermal methods.[B2] ETFE films are often called with commercial names given by the manufacturer.

4.2.1.1 ETFE film mechanical properties

ETFE is an isotropic material. Due to the production method, there is a difference between the extrusion and the opposite direction. This difference is negligible because it is too little.[PR] Its distribution of crystalline and amorphous regions is statistically approximately equal.
ETFE exhibit nonlinear visco-elastic material behavior. The mechanical behavior of the ETFE can be examined in three different regions.[M4]

• Linear elastic deformation (Region 1)
The reason for the deformation is the change in the distance and angle between the molecules. This deformation is reversible. Hooks Law is valid at this region for short-term loads. The elastic limit varies depending on the temperature and duration of the load.[M4] ETFE foil show lianer-elastic behavior up to a stress of 15Nmm²
(200µm, 23°C, Nowofol).[PR]

The material in the elastic region acts as a spring. When the tensile load release, the spontaneous elongation disappears, and the material returns to the initial geometry. Linearity refers to the constant stress-strain ratio in this region. The stress-strain graph follows the same path when the applied load to the elastic material is repeated. The targeted operating stress for ETFE is within the limits of the linear elastic region.

• Linear and nonlinear visco-elastic deformation (Region 2)

Thermoplastic materials basically show viscous behavior.[B2] Viscosity is the resistance of a material to flow. The deformation of a material exhibiting visco-elastic behavior, continues with time. When a constant tension is applied above the elastic limit, ETFE exhibits visco-elastic behavior. The reason for this behavior is that the entangled polymer chains change shape under tension. This deformation is partially reversible depending on the time.[M4] Permanent deformation starts at 23°C, 21N/mm² (50-300μm).[M1]

• Visco-plastic deformation (Region 3)

ETFE loses load bearing capability in this region. It shows great deformation under low-level load. Plasticity refers to the permanent deformation of the material. When the load is removed the material never returns to its original size. The reason for this is that the molecular chains that constituting the material, slide over one another.[M4] This action continues until the material breaks. The tensile strength of ETFE is at 23°C, 48N/mm² in short-term tests.[M1] Its elongation at break point can exceed 600%.

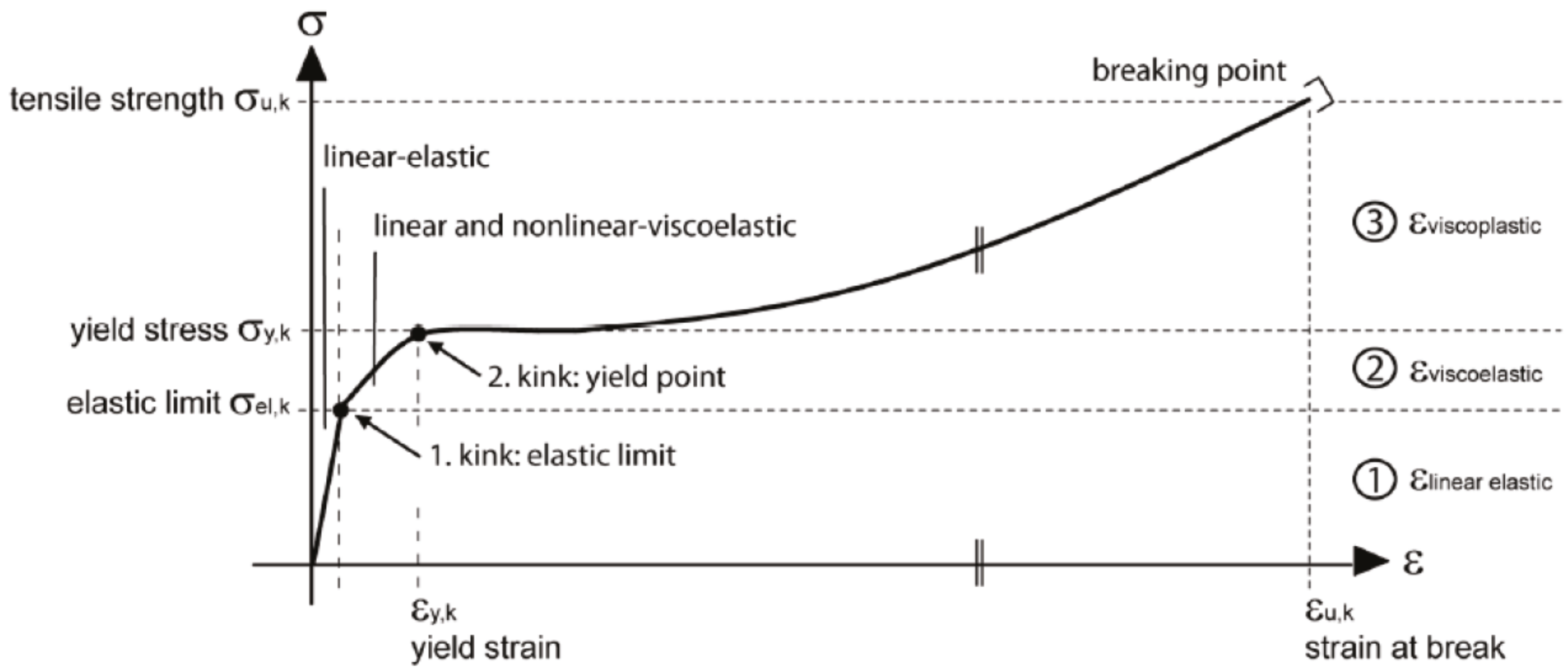
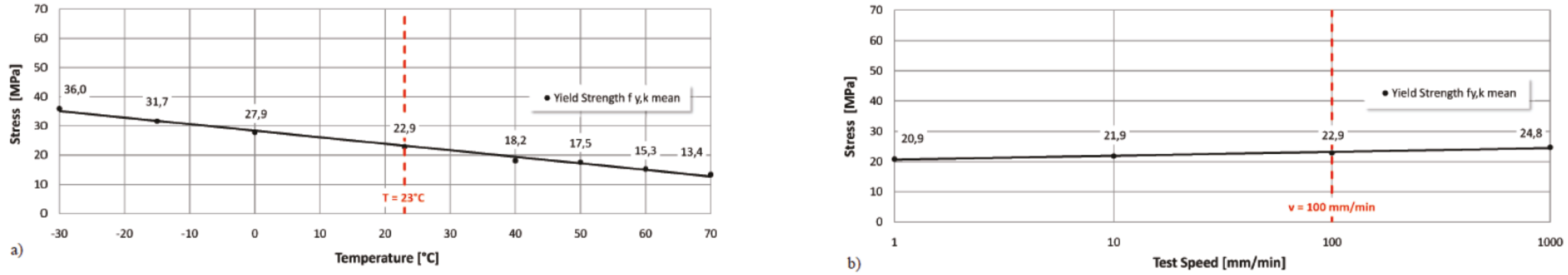


Figure 2.10 Mechanical behavior of ETFE film (Source [M1])

4.2.1.2 Time Temperature Shift

The modulus of elasticity of the typical amorphous polymer increases with the loading speed and decreases with increasing temperature.[WS] The effect of temperature and time on the visco-elastic thermoplastic material is called "Time Temperature Shift" (TTS). The mechanical behavior of the ETFE and the load carrying capacity depends on the temperature and the speed of the load. These factors have opposite effects on the yield strength and elastic modulus of the material. An ETFE cushion is exposed to the wind and snow load. These loads have different characteristics in terms of temperature and speed. The snow load occurs at low temperature and at a low speed. The wind load is generated at a rapid rate in hot or cold weather.[M2] The relationship between temperature and load velocity is shown in the following test results. Between -10 and + 40°C, the material loses roughly 40% strength. (Figure 2.11.a) (-10°C = 30N/mm², +40°C = 18N/mm²)



(a) Effect of temperature *(b) Effect of load rate*

Figure 2.11 The effect of temperature and load rate on the ETFE mechanical behavior (Source [M2])

ETFE cannot heat up more than 50°C due to solar radiation. In the simulations taking into account the worst conditions, the highest measured temperature is 48.5°C.[PR]

4.2.2 THV film

It is a thermoplastic from the Fluoropolymer family.

It is a flexible material such as ETFE. It has low tear resistance. For this reason, it is not suitable for a wide span. Produced from 0.08mm to several mm thickness.[M5] It is an easy plastic to process. It is formed by the combination of three different fluoropolymers. The light transmittance for 100µm is 97%. The usage temperature is lower than ETFE.[KN] Architectural use is rare due to its weak mechanical properties. It can be welded with high frequency.[BC] The breaking strength is 22/21 N/mm² (DIN53455). Its elongation at break point is 540/560%. It has B1 class non-flammability properties (DIN 4102). Its economic life is more than 20 years.[HR] THV is also used as a coating material on a ETFE and PTFE fabric weave.[ML]

Part III

Architectural design

“It is interesting to note that good structures often show a readable flow of forces, perhaps because they are easy to understand and because we like what we understand. Elegant structures are often lightweight structures”.[SH]

5.1 Design concept

Within the scope of the thesis, a tensile membrane structure which is carried with a cantilever construction was designed. The reason for choosing a cantilever system as a design example is that although those systems are relatively small, their's design, analysis and detailing process require special attention. Because, these structures are sensitive to external loads. Also, the cantilevered systems are more open to architectural and structural creative design solutions. The general aim of the design is to develop a general alternative for the areas where the cantilever system is necessary. The designed system can be used for different purposes. The targeted cantilever span is around 6-7m.

The basic concept of design is that the system is architecturally "rich" and structurally "effective". The term "rich" refers to increasing the total number of components by splitting the elements that constituting the load carrier system. From a different point of view, the "rich" expression can be considered "complicated" due to the increased number of elements. The expression "effective" means to arrange a certain amount of material in such a way as to maximize the stability and strength of the load carrier system. Both goals are consistent with each other.

A cantilever system is generally applied for functional reasons instead of aesthetic requirements. In some areas, this kind of solutions are necessary for efficient use of the structure. Car parks, viewing and waiting areas, swimming pool edges are examples of such areas. The common feature of that areas is that they have a usage direction. Naturally, the direction of the console is the front part of the structure. In that kind of area, the presence of a mast at the front side, prevents the structure from being used efficiently. In a cantilever systems, the structure is carried by a mast at the edge. An asymmetrical structure that has single mast requires larger sections to resist wind and snow loads. A cantilever span limit can change depend on the components of the load carrier system. For example, the maximum cantilever span that can be achieved with the construction shown in figure 3.2.e is larger than the system shown in figure 3.2.a.

An object is always part of a whole. The same object can have a different meaning when it came to side with different objects. In this context, the claim of the architectural suitability for an isolated design is meaningless. The architectural suitability decision of an object should be given by the person who knows the whole. But, the consistency between the components of an designed object can be evaluated independently from its isolation. What do we see when we look at the constructions in figure 3.1? A vertical mast, three linear inclined suspension arm, and a curved arch beam. The curvature of the arch beam and the linearity of the suspension arms are a necessity. Considering the harmony of the elements, an inclined mast may increase the architectural consistency.

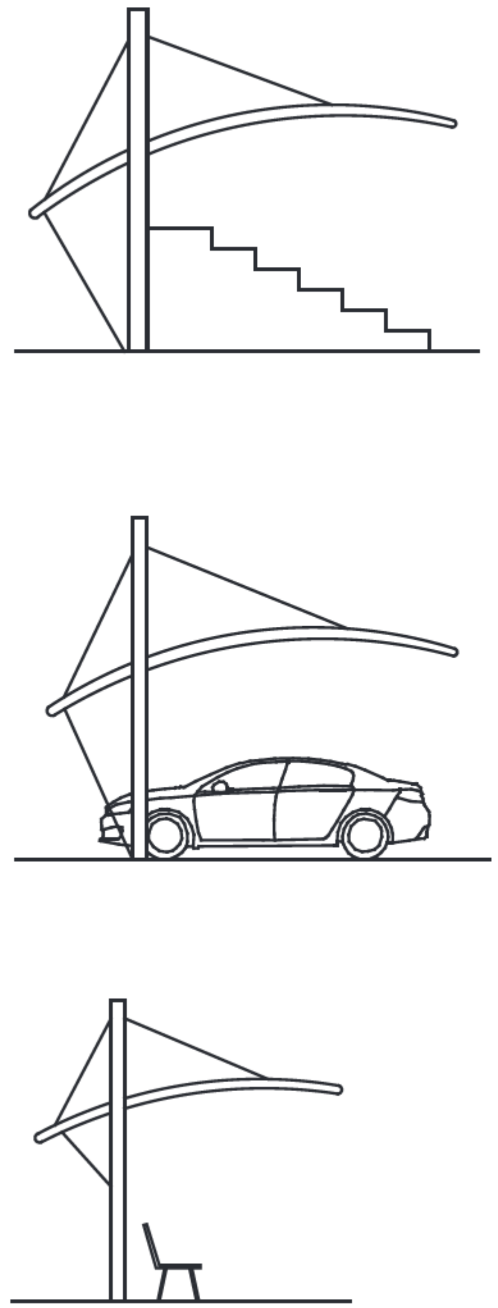


Figure 3.1
Cantilevered arch applications

A membrane surface adjusted to the cantilever systems is usually in the arch form. (Figure 3.2) In this kind of solution, the console beam is shaped like an arch. The opposite curvatures of the membrane surface are provided by this arch beam. The amount of curvature on the membrane surface depends on the arch geometry. As the curvature of the cantilever increases, the curvature of the membrane surface increases, and thus the stability of the membrane surface increases. However, the stability of the cantilever beam is reduced. The optimum solution is investigated during the design and analysis phase.

The support system of an arched cantilever membrane structure can be examined in two parts that are vertical and horizontal. The vertical part consists of a column and an inclined arch beam. The horizontal section consists of compression elements which connects the vertical systems together. Design alternatives for the compression elements in the horizontal direction are limited. The changes to be made in the horizontal direction are not important enough to affect the architectural character of the structure.

The structural capacity and architectural character of a cantilever system are determined by the vertical elements. The vertical part of the structure consisting of the column and the beam can be designed in different ways in terms of architectural and structural requirements. Because of the console, the mast and arch beam is subjected to a high bending moment. Firstly, the structural design must cope with this moment. I and H variable section profiles are usually the first choice because of a high bending moment for load carrier system. However, all profiles used in this design example have circular section because of architectural consistency. Furthermore, the circular cross section provides an advantage in terms of torsion. Espetially, this advantage is important for the cantilever construction mast.

By adding new elements to the construction, the system can be improved structurally and architecturally. Figure 3.2 shows that how the load carrying system which consisting of two element is turned into structurally more "effective" and architecturally more "rich" by adding new elements. Each of the five systems shown in figure 3.2 is consistent and applicable. Each of the construction can be chosen for different reasons. For the thesis, the construction in figure 3.2.d was selected as a design example.

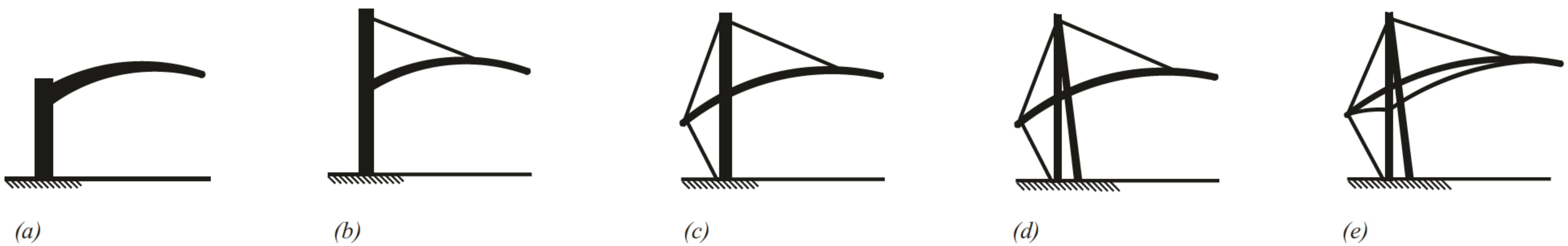


Figure 3.2 The constructions getting more architecturally “rich” and structurally “effective”

The limit of the span getting more large “a” to “e”.

5.2 Detailing concept

The connection between membrane and steel construction is one of the most important details at the membrane structures. All the loads coming form membrane surface are transferred to the steel construction by this connection. This connection details affect the profile type and section dimensions, especially in the rigid edge frame systems. When designing steel constructions, this detail should be determined first. That connection detail for this design example is shown in figure 3.4.

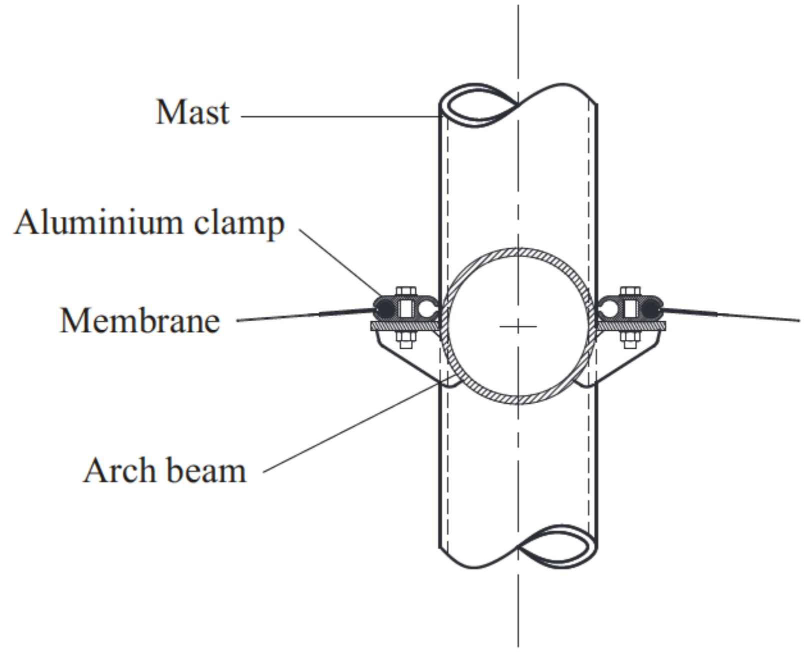


Figure 3.4 The connection between membrane rigid edge and steel frame (The membrane edge aluminum profile flow without interrupt around the mast.)

In this design example, it is aimed that the membrane must continue along the arch beam without an interruption. An interruption around the mast causes a visual disturbing appearance. Furthermore, when the membrane is exposed to a load, unpredicted stresses may occur due to deformation in this region. If the high deformation capability of the membrane surface considered, the details of such points are important. The continuous flow of the membrane along the arch beam can be provided if the diameters of the mast and the arch profile are the same. It is obvious that the mast needs a larger section than the arch beam need. At this approach, the mast and arch beam connection point is a potential problem reason. Figure 3.3.a shows this problem. Figure 3.3.b,c,d show possible logical solutions.

The vertical support system used in the design as a solution consists of two masts. With this way, it is possible to equalize the diameters of the mast and arch beam. (Figure 3.3.d)

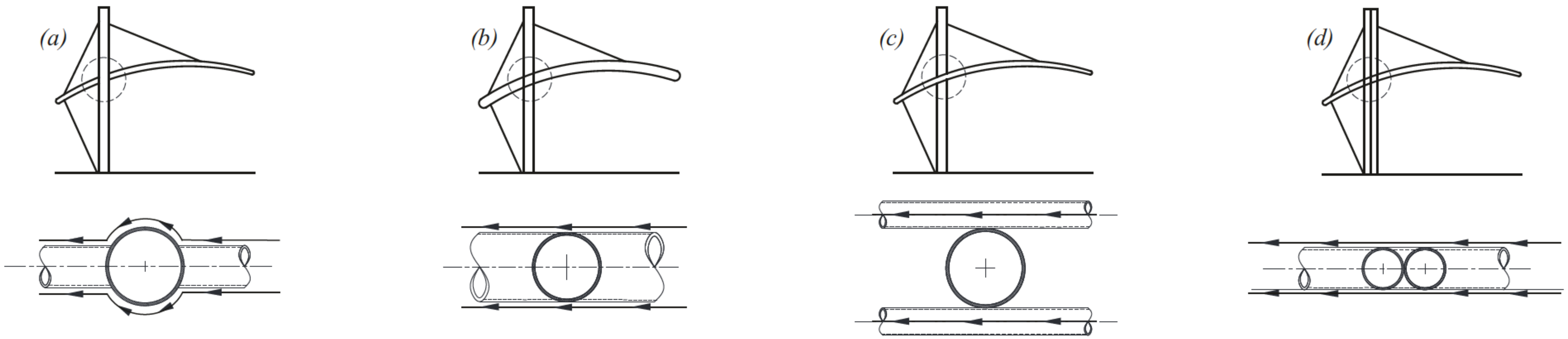


Figure 3.3 The illustration of the arch and mast connection (The arrow represents the membrane edge flow)

5.3 Description of the structure

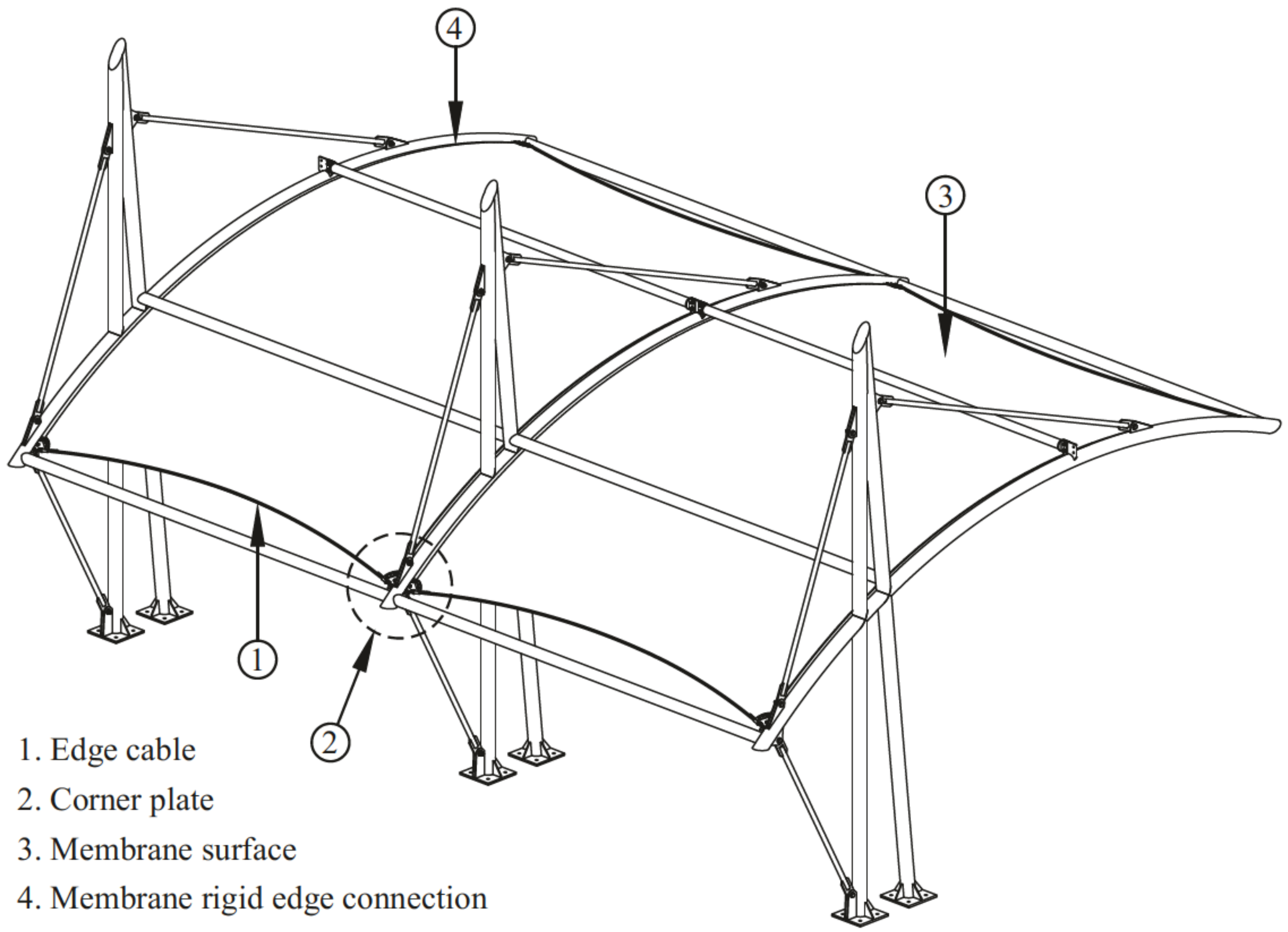
The designed cantilevered arch structure consists of modules. By adding new modules to the system, the length of the structure can be increased. One module consists of two vertical load bearing construction connected each other by four compression beam. The vertical load bearing units are positioned parallel to one another in this design example. But they can be positioned in a circular manner. The area is covered with a membrane between two arch beams. The membrane was fixed in two sides to the arch beam using an aluminium channel. The membrane surface was terminated with steel cables on the other two sides. Prestress is provided by means of these cables on the surface. There are corner plates on the four corners of the membrane surface. Stresses generated in the cables are transferred to the steel construction via these corner plates.

One module of the system consists of two vertical masts, three hanging trusses, and an arch beam. Loads generated in the console beams are transferred to the concrete bases via suspension trusses. A circular cross-section was used for suspension trusses profile. If the wind applies internal pressure or exterior suck, compression occurs in the suspension trusses. For this reason, a cable cannot be used as a suspension element.

Cross bracing elements can be added to the construction in the horizontal direction. These connections increase the stability of the structure. However, these elements may prevent sliding of snow from the membrane surface.

When defining the span between the two masts, the width was taken into account which two cars would stay together. Increasing or decreasing this span, affects the degree of curvature of the membrane surface. As the span increases, the surface curvature decreases. All the details used in the system are portable. Considering the final appearance of the construction, the details which connecting the arch beam to the mast can be covered. The same visual requirement is valid for base plates. That plates should stay under the finished floor.

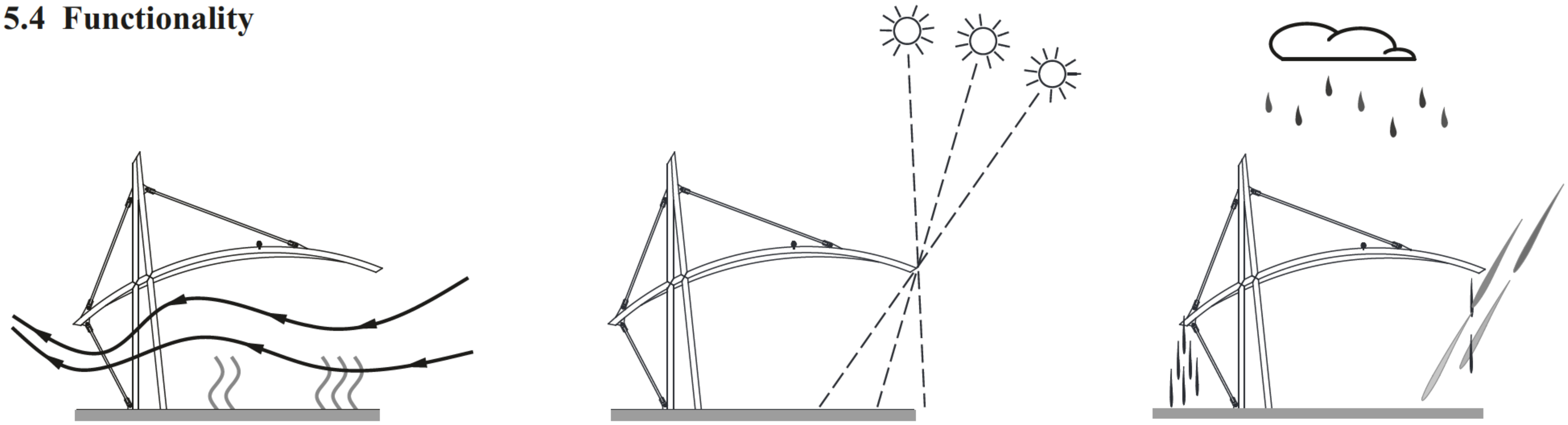
The membrane surface consists of six panels in total. The predicted membrane material is PVC/PES Type 2.



1. Edge cable
2. Corner plate
3. Membrane surface
4. Membrane rigid edge connection

Figure 3.5 3D view of two modules.

5.4 Functionality



(a) (b) (c)

Figure 3.6 The membrane structure under environmental effects

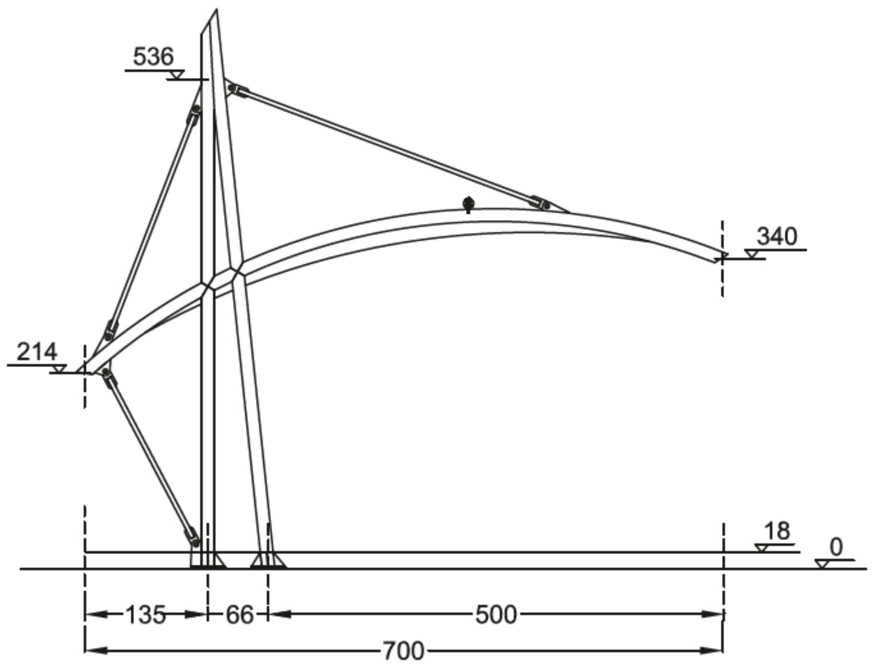
The length of the structure depends on number of the modules. For this reason, the environmental effects only at the console direction were taken into account.

The ambient temperature in a shaded area is expected to be less. To use heat holding materials in the construction, increases temperature felt in the shadow. A membrane is a material that does not hold heat in this sense, it reflects the rays of the sun in great amount. The steel construction warms up and spreads heat. This situation is also valid for the floor covering material. In hot climates, increasing the total height of the structure and using heat-reflecting materials to cover the floor helps reduce the temperature in the shadow. At the back side of the building, the height is about two meters. Especially in hot climates, this space is important for the circulation of the heated air. Setting a wall or plant etc. to the front of this space may prevent air circulation.

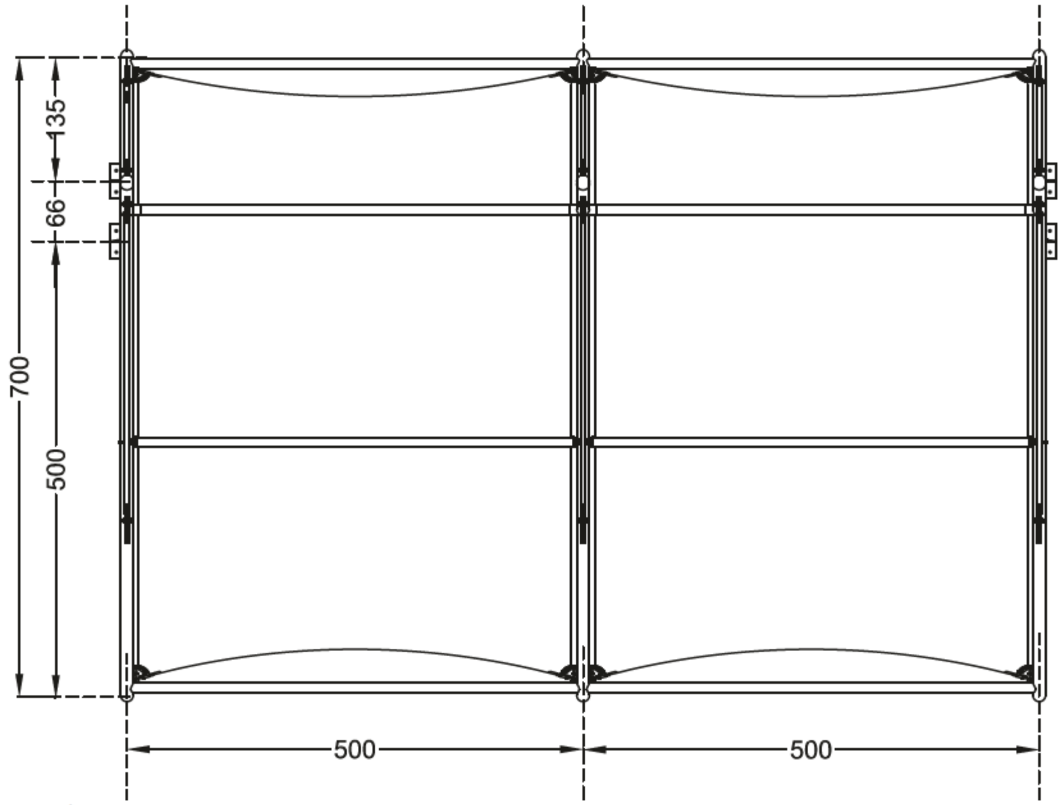
If it possible, the direction of the structure should be determined according to the movement of the sun, at the planning stage. The maximum shade is provided when the front of the structure is facing to north. If shading is a priority requirement and the building is obliged to look to south, the desired shadow cannot be achieved. Changing the console inclination may reduce the problem.

The height is increasing towards the front side. The aim of this slope is to keep rain and snow water away from the front of the structure as much as possible. The snow and rainwater coming from the membrane surface are gathering on the back side of the structure. Evacuation of rainwaters with a drainage system provides a less wet floor. The concrete foundations are located in this area where rainwater is collected. If the system is installed in the green space, the structural safety of the foundations must be taken into account in the design phase. The front side of the structure gets wet because of the rain that comes with the wind.

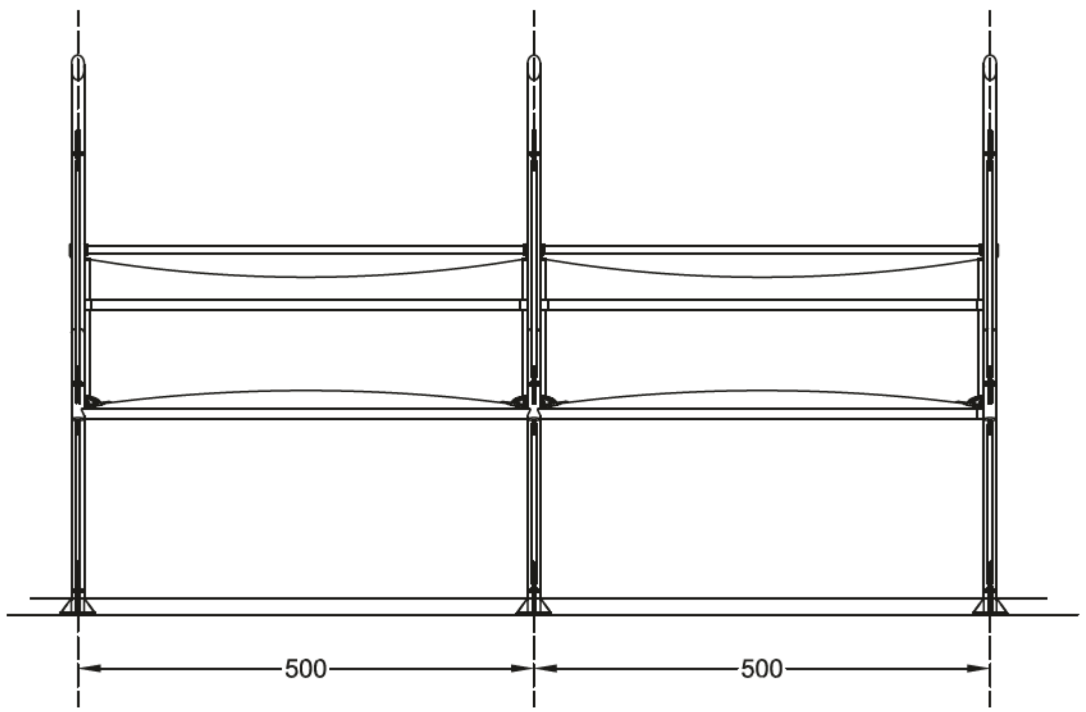
5.5 Geometry of two modules



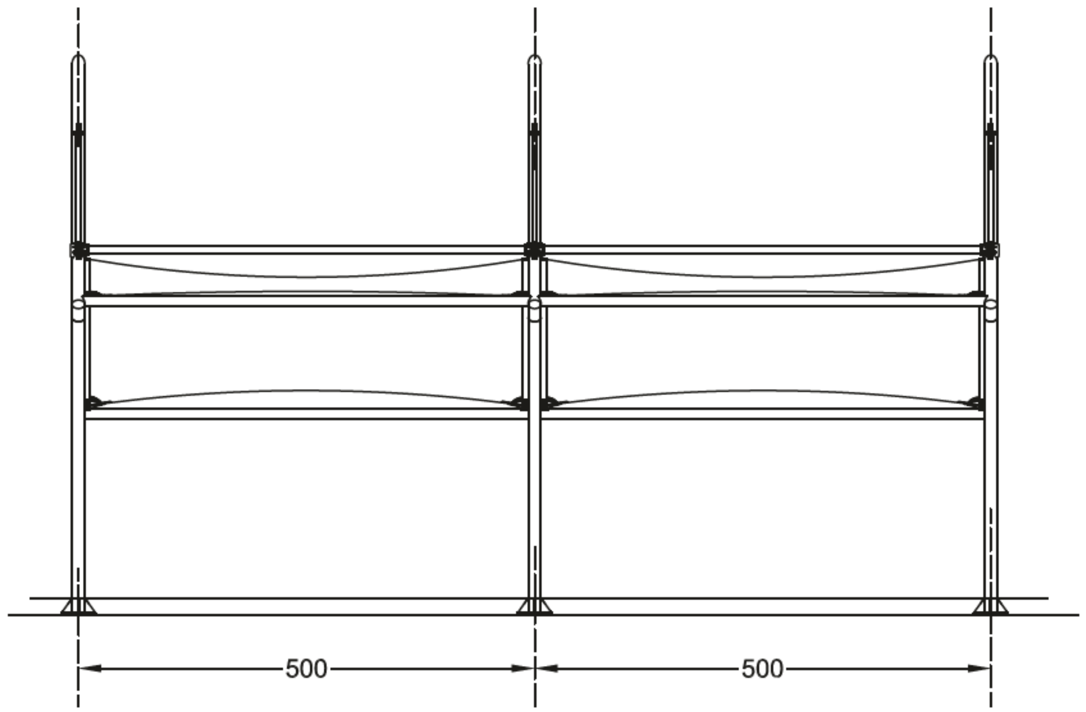
Side view



Top view



Back view



Front view

All dimensions are in cm.

Part IV

Structural design and detailing

“Despite modern computational methods there are still open questions in the numerical modeling of tensile structures. Form finding, cutting pattern generation, transient load conditions (e.g. wind loads) and appropriate material modeling introduce questions ...” [DR]

6.1 Wind load

The wind load acting on the membrane surface was determined according to the EN 1991-1-4. When describing the CP values Autodesk Flow Design (AFD) was used.

(1) Basic wind velocity : v_b

vb_0 : Basic wind speed $28m/s$

$$v_b = C_{dir} \cdot C_{season} \cdot vb_0 \rightarrow 1 \cdot 1 \cdot 28 = 28m/s$$

(2) Terrain factor : k_r

$$z_{\min} = 5m,\ \ z = 4m \rightarrow z \leq z_{\min}$$

$$z_0 = 0.3m,\ \ z_{0,u} = 0.05m,$$

$$k_r = 0.19 \cdot \left(\frac{z_0}{z_{0,u}}\right)^{0.07} \rightarrow 0.19 \cdot \left(\frac{0.3}{0.05m}\right)^{0.07} = 0,215$$

(3) Roughness factor : $c_r(z)$

$$c_r(z) = k_r \cdot \ln\left(\frac{z_0}{z_{0,u}}\right) \rightarrow 0,215 \cdot \ln\left(\frac{5}{0,3}\right) = 0,605$$

(4) Main wind velocity : $v_m(z)$

$$c_o(z) = 1$$

$$v_m(z) = c_r(z) \cdot c_o(z) \cdot v_b \rightarrow 0,605 \cdot 1 \cdot 28 = 16,94m/s$$

(5) Turbulence intensity : $I_V(z)$

$$k_1 = 1$$

$$I_V(z) = \frac{k_1}{c_o(z) \cdot \ln\left(\frac{z_{\min}}{z_0}\right)} \rightarrow \frac{1}{1 \cdot \ln\left(\frac{5}{0,3}\right)} = 0,355$$

(6) Peak velocity pressure : $q_p(z)$

$p = 1.25kg/m^3$ (air density)

$$q_p(z) = \left[\left(1 + 7 \cdot I_V(z)\right)\right] \cdot \frac{1}{2} \cdot p \cdot v_m(z)^2 \rightarrow$$

$$\left[\left(1 + 7 \cdot 0,355\right)\right] \cdot \frac{1}{2} \cdot 1,25 \cdot 16,94^2 = 625,043\ N/m^2$$

(7) Wind pressure acting on the external surface: W_e

$$W_e = q_p(ze) \cdot C_{pe}$$

6.1.1 Wind flow direction (X+)

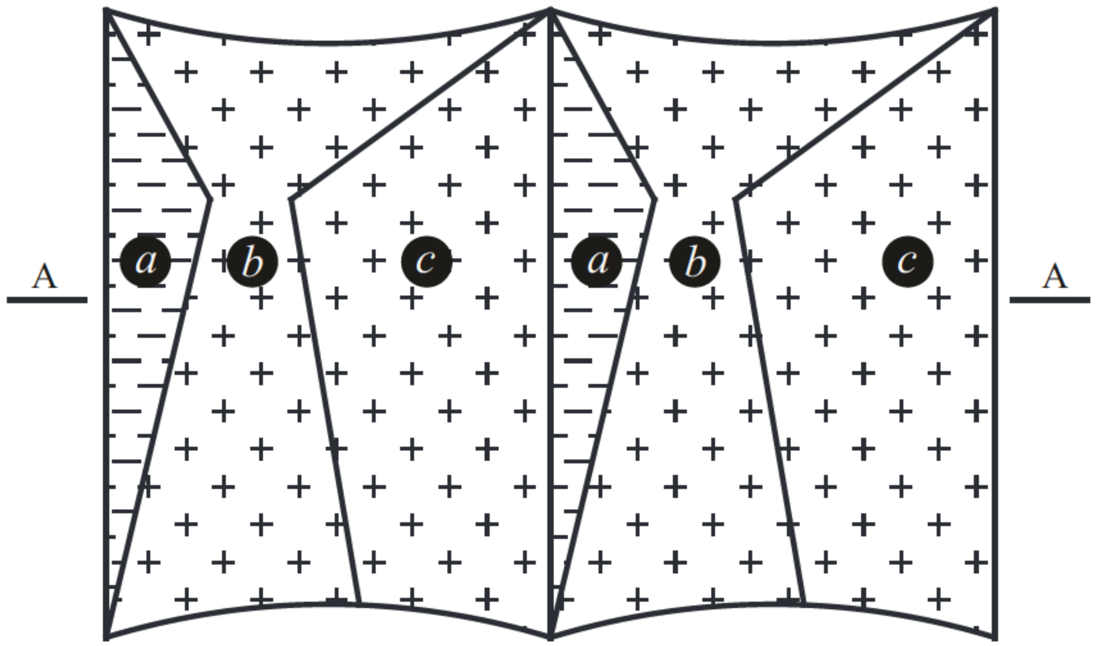


Figure 4.1.a Wind action on the exterior side of the surface

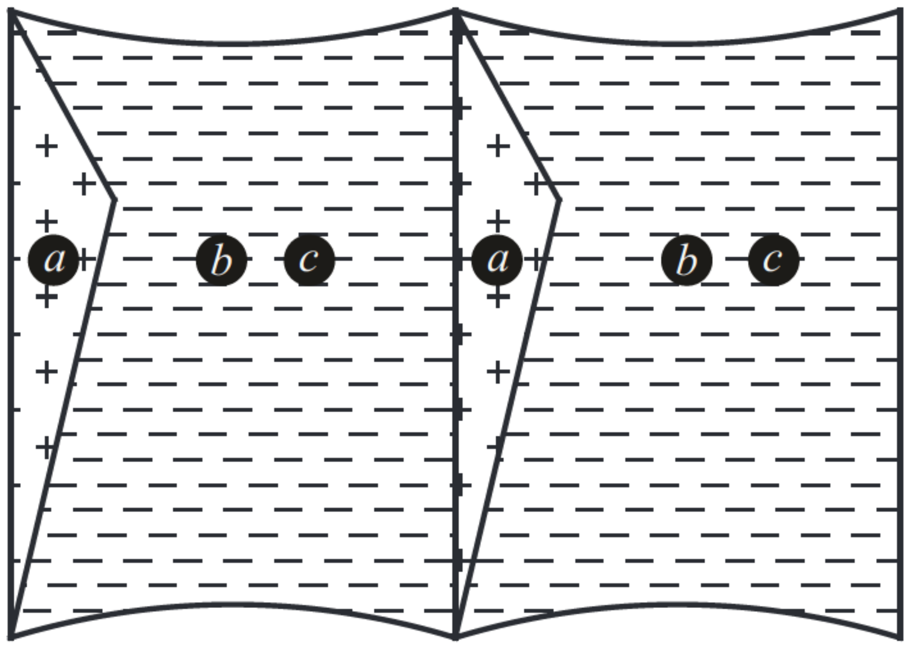


Figure 4.1.c Wind action on the interior side of the surface

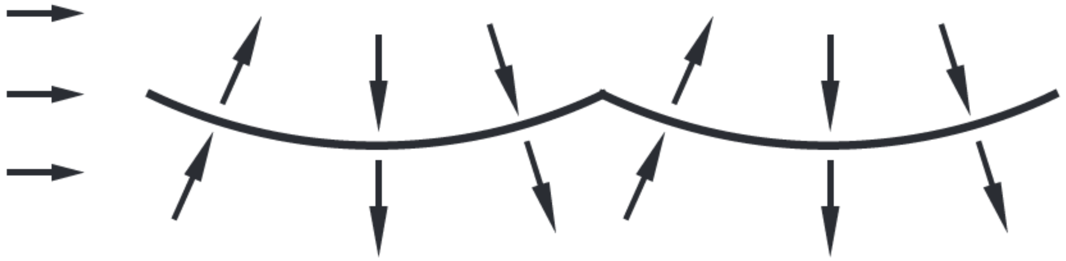


Figure 4.1.b Wind pressure directions in the A-A section

Part	a	b	c
Exterior pressure	-150	75	125
Interior pressure	150	-100	-100

Table 4.1.a The pressure values from AFD value (Pa)

Part	a	b	c
Cpe	-0,31	0,15	0,26
Cpi	0,31	-0,20	-0,20
Cpnet	-0,62	0,35	0,46

Table 4.1.b The derived Cp values

6.1.2 Wind flow direction (Y+)

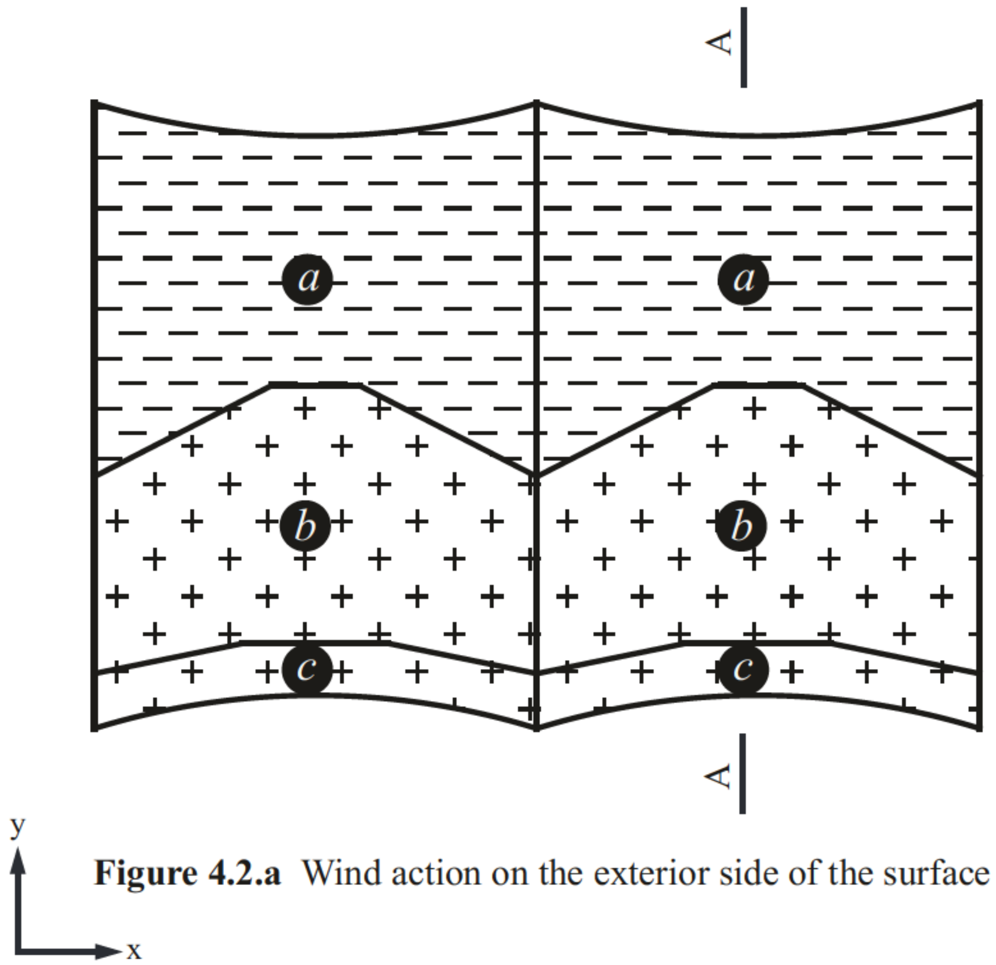


Figure 4.2.a Wind action on the exterior side of the surface

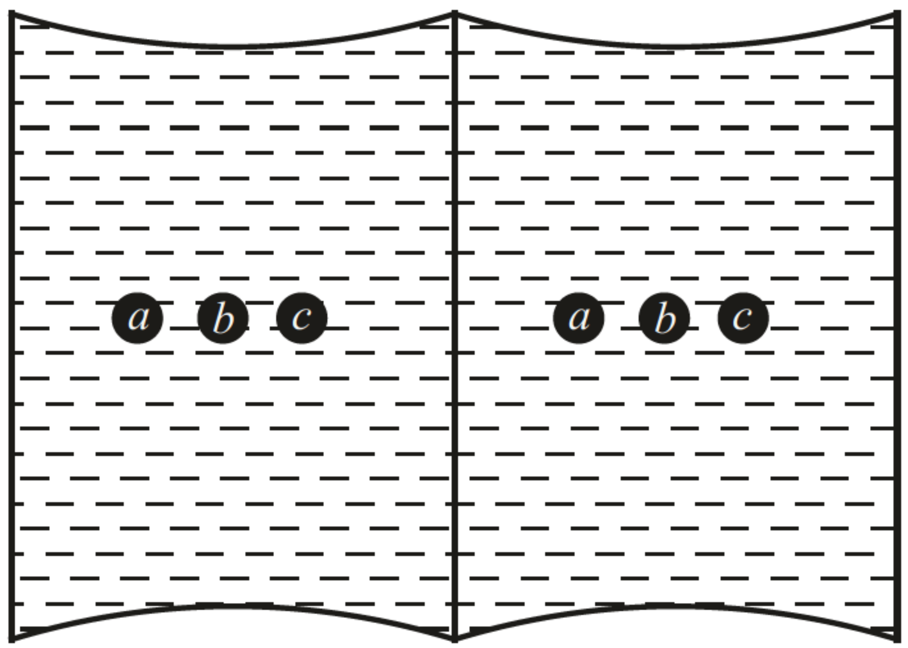


Figure 4.2.c Wind action on the interior side of the surface

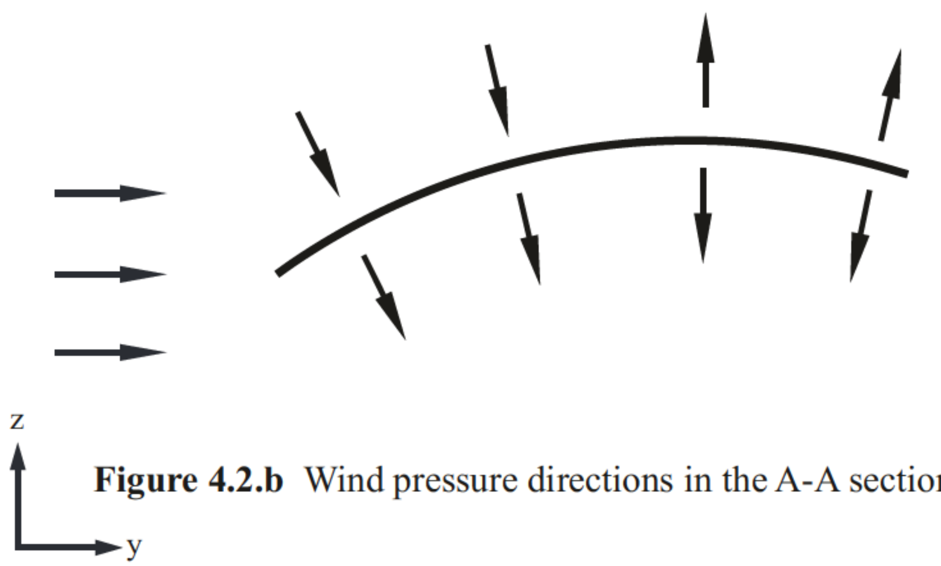


Figure 4.2.b Wind pressure directions in the A-A section

Part	a	b	c
Exterior pressure	-250	200	400
Interior pressure	-150	-150	-150

Table 4.2.a Pressure value from AFD value (Pa)

Part	a	b	c
Cpe	-0,51	0,41	0,82
Cpi	-0,31	-0,31	-0,31
Cpnet	-0,20	0,72	1,13

Table 4.2.b The derived Cp values

6.1.3 Wind flow direction (Y-)

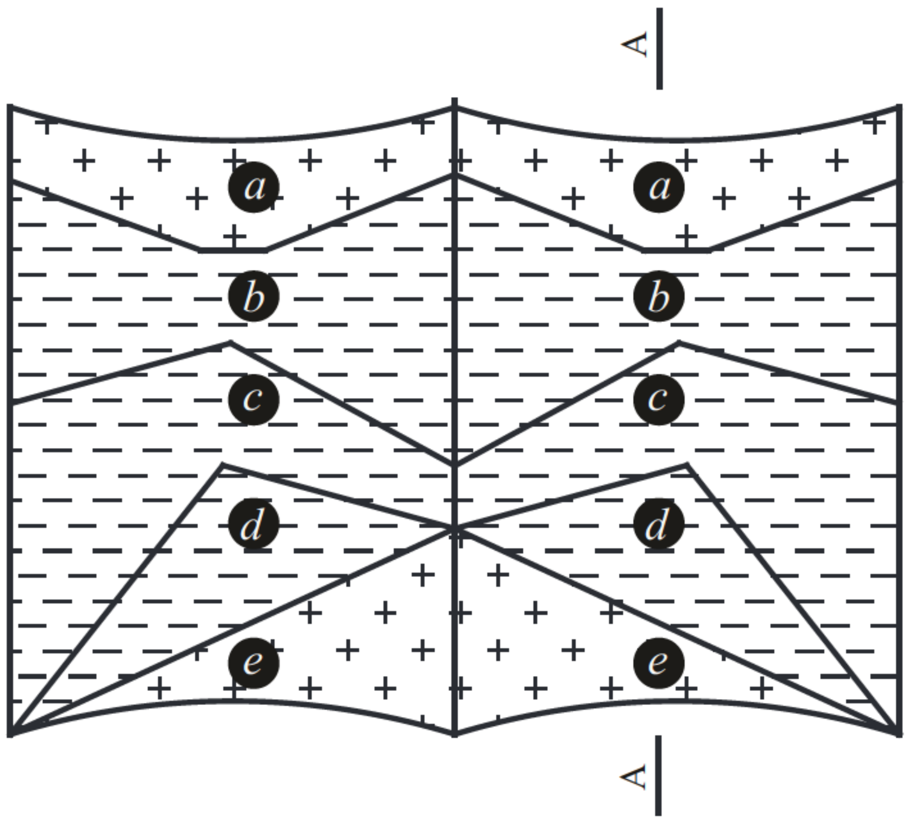


Figure 4.3.a Wind action on the exterior side of the surface

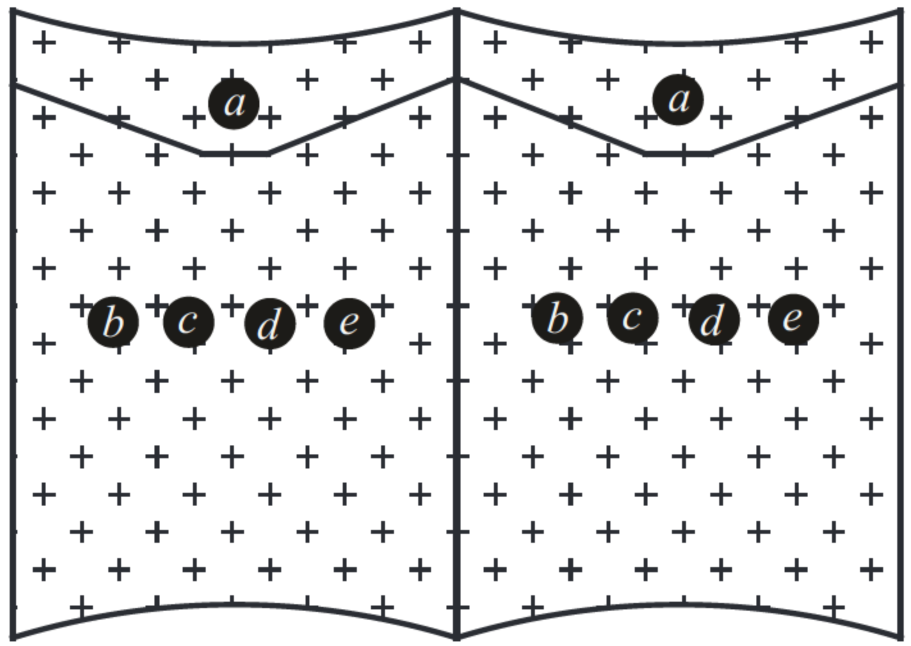


Figure 4.3.c Wind action on the interior side of the surface

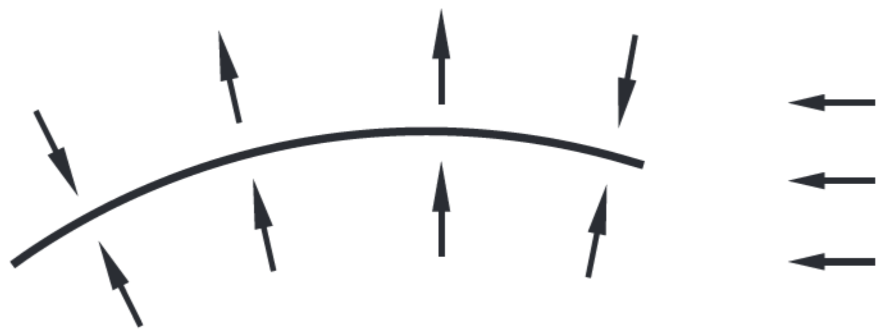


Figure.4.3.b Wind pressure directions in the section A-A

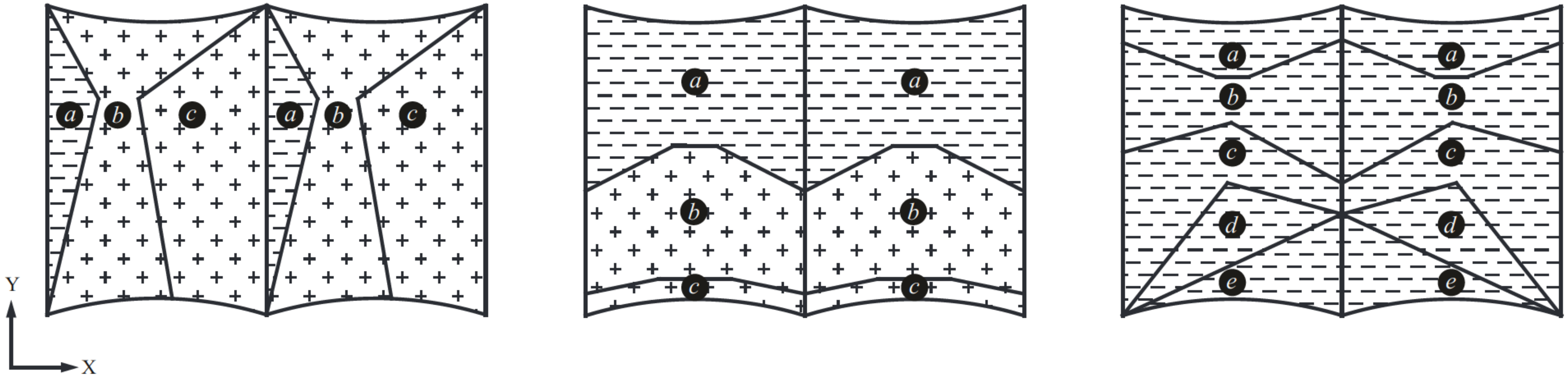
Part	a	b	c	d	e
Exterior pressure	100	-150	-500	-300	50
Interior pressure	150	300	300	300	300

Table 4.3.a Pressure value derived from AFD value (Pa)

Part	a	b	c	d	e
Cpe	0,20	-0,31	-1,02	-0,61	0,10
Cpi	0,31	0,61	0,61	0,61	0,61
Cpnet	-0,11	-0,92	-1,63	-1.22	-0,51

Table 4.3.b The derived Cp values

6.1.4 CP values



(a) Wind pressure pattern (X+)　　*(b) Wind pressure pattern (Y+)*　　*(c) Wind pressure pattern (Y-)*

Figure 4.4 Illustration of wind actions on the membrane surface

(X+)	(Y+)	(Y-)
a) -0,39	a) -0,13	a) -0,07
b) 0,22	b) 0,45	b) -0,58
c) 0,29	c) 0,71	c) -1,02
		d) -0,76
		e) -0,32

Table 4.4 Final wind pressure on the membrane surface kN/m² (W_e)

Note:

1) *The CP value patterns were prepared according to the AFD values. The source of patterns was attached to the thesis annex.*
2) *To draw more detailed wind CP patterns are possible, especially at the wind Y negative direction. The CP patterns was drawn roughly staying on safe side.*
3) *According to AFD results, generally interior and exterior pressure are overlapping. Some unimportant deviation was ignored.*
4) *The structure is not symmetrical. Therefore, the diagonal wind influence on the structure must be investigated separately.*

6.2 Snow load

The snow load was described according to the EN 1991-1-3.

$$S = \mu_i \cdot C_e \cdot C_t \cdot S_k$$

$S =$ Snow load on the roof (kN/m²)

$\mu_i =$ Snow load shape coefficient

$C_e =$ Exposure coefficient

$C_t =$ Thermal coefficient

$S_k =$ Characteristic value of snow load (kN/m²)

Characteristic snow loads are changes according to the height of the ground of the structure from sea level, and zone of the structure. According to the TS EN1991-1-3, there are four different zones. The structure ground was assumed not height than 1000m and the structure located is in the zone 2. The characteristic snow load value for these properties is 0,75kN/m².

$\mu_i = 0,8$ (Table 5.2)

$C_e = 1,2$ (Table 5.1)

$C_t = 1$ (The structure sides is not closed.)

$S_k = 0,75 kN/m^2$

$S = 0,8 \cdot 1,2 \cdot 1 \cdot 0,75 = 0,72 kN/m^2$

-The membrane surface inclination is less than 30 degree.
-It was assumed that there is no obstacle to sliding snow from surface.
(In reality, the compression beams can prevent sliding of snow)

The inclination is less on the front side of the membrane surface. For this reason, when the snow slips off the inclined part of the surface, there may still be snow on the front of the membrane. If the cantilever construction properties considered, this unbalanced snow load distribution can have a critical effect on the structure. For this reason, snow load will be investigated in two different load conditions. In cases where the snow load is important, more negative loading scenarios can be considered.

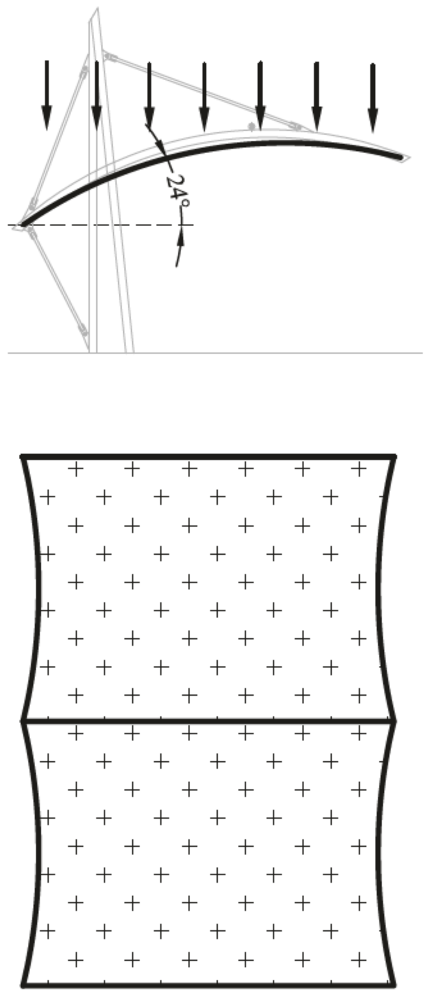


Figure 4.5.a
Full snow load (FS)

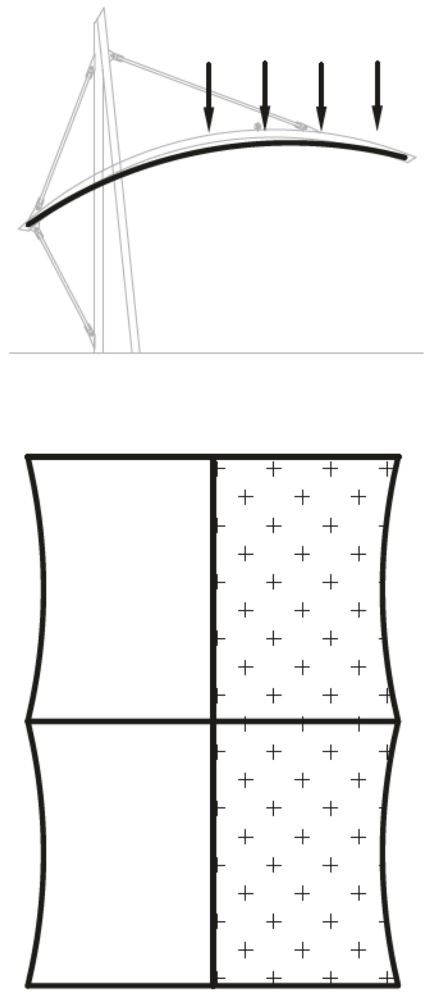


Figure 4.5.b
Partial snow load (PS)

6.3 Load combinations

According to the EN 1990, basic load combination for permanent and transient design situations is as below.

$$\sum_{j\geq 1}\gamma_{G,j}\cdot G_{k,j}+\gamma_{p}\cdot p_{k}+\gamma_{Q,1}\cdot Q_{k,1}+\sum_{i\geq 1}\gamma_{Q,i}\cdot \psi_{0,i}\cdot Q_{k,i} \quad \text{(Eq. 6.10)}$$

γ_G = Partial factor for permanent actions,

G_k = Characteristic value of a permanent action

γ_P = Partial factor for prestressing actions

P_k = Characteristic value of a prestressing action

$\gamma_{Q,1}$ = Partial factor for permanent action j

$Q_{k,1}$ = Characteristic value of the leading variable action 1

$\gamma_{Q,i}$ = Partial factor for variable action i

$Q_{k,i}$ = Characteristic value of the accompanying variable action i

$\psi_{0,i}$ = Factor for combination value of a variable action

The actions effecting the structural model are,

G = Self weight (Permanent Action - Dead load)

p = Prestress (Permanent action - Dead load)

Q_W = Wind ((Variable Action- live Load)

Q_S = Snow (Variable Action- live Load)

$\gamma_{G,j}=1{,}35$ (Table A1.2B)

$\gamma_{Q}=1{,}5$ (Table A1.2B)

$\psi_{0,i}=0{,}5-0{,}7$ Snow (Table A1.1)

$\psi_{0,i}=0{,}6$ Wind (Table A1.1)

The load combination for singular variable action which wind or snow

$$1{,}35\cdot G+1{,}35\cdot p+1.5\cdot Q_W \ \ or \ \ Q_S$$

The load combination in case snow and wind affecting the structure together in addition to the permanent action

In case, wind is leading variable action,

$$1{,}35\cdot G+1{,}35\cdot p+1.5\cdot Q_W+1{,}5\cdot 0{,}7\cdot Q_S$$

In case, snow is leading variable action,

$$1{,}35\cdot G+1{,}35\cdot p+1{,}5\cdot Q_S+1{,}5\cdot 0{,}6\cdot Q_W$$

ENV 1993-1-1:1992 is including simplified approach in case two or more variable action effecting the structure. (This standard is not in effect)

$$\sum_{j}\gamma_{G,j}\cdot G_{k,j}+0,9\cdot\sum_{i\geq 1}\gamma_{Q,i}\cdot Q_{k,i} \qquad \text{(EC3 2.3.3)}$$

$$1,35\cdot G+1,35\cdot p+0,9\cdot\sum 1.5\cdot Q_{W}+1,5\cdot Q_{S}\rightarrow$$

$$1,35\cdot G+1,35\cdot p+1,35\cdot Q_{W}+1,35\cdot Q_{S}$$

The Ultimate Limit State (ULS) load combinations were constituted according to the EC3 2.3.3.

	G	p	WXP	WYP	WYN	FS	PS
ULS LC1	1,35	1,35	1,5	-	-	-	-
ULS LC2	1,35	1,35	-	1,5	-	-	-
ULS LC3	1,35	1,35	-	-	1,5	-	-
ULS LC4	1,35	1,35	-	-	-	1,5	-
ULS LC5	1,35	1,35	-	-	-	-	1,5
ULS LC6	1,35	1,35	1,35	-	-	1,35	-
ULS LC7	1,35	1,35	-	1,35	-	1,35	-
ULS LC8	1,35	1,35	-	-	1,35	1,35	-
ULS LC9	1,35	1,35	1,35	-	-	-	1,35
ULS LC10	1,35	1,35	-	1,35	-	-	1,35
ULS LC11	1,35	1,35	-	-	1,35	-	1,35

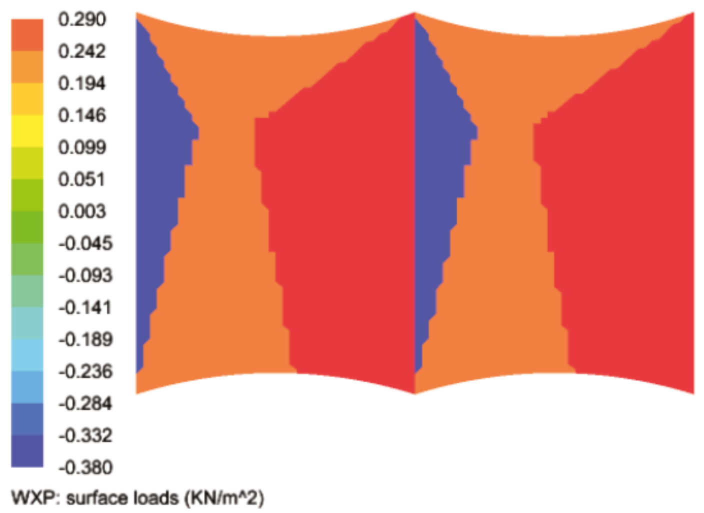
Table 4.5.a ULS combinations

	G	p	WXP	WYP	WYN	FS	PS
SLS LC12	1	1	1	-	-	-	-
SLS LC13	1	1	-	1	-	-	-
SLS LC14	1	1	-	-	1	-	-
SLS LC15	1	1	-	-	-	1	-
SLS LC16	1	1	-	-	-	-	1
SLS LC17	1	1	1	-	-	1	-
SLS LC18	1	1	-	1	-	1	-
SLS LC29	1	1	-	-	1	1	-
SLS LC20	1	1	1	-	-	-	1
SLS LC21	1	1	-	1	-	-	1
SLS LC22	1	1	-	-	1	-	1

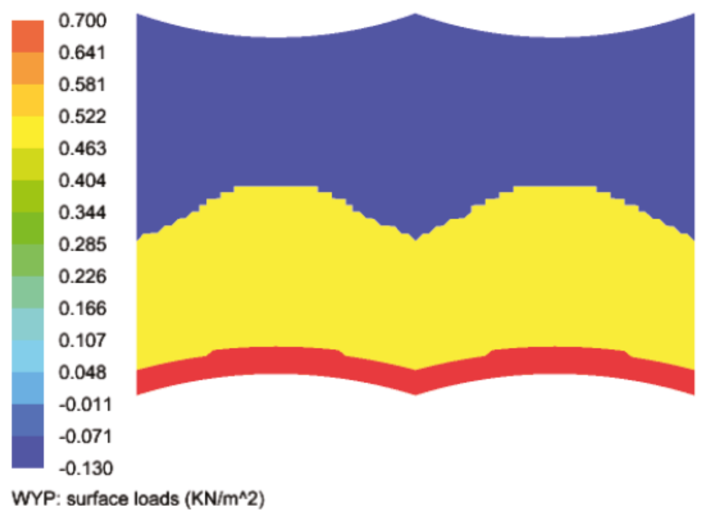
Table 4.5.b SLS combinations

6.4 Applied loads

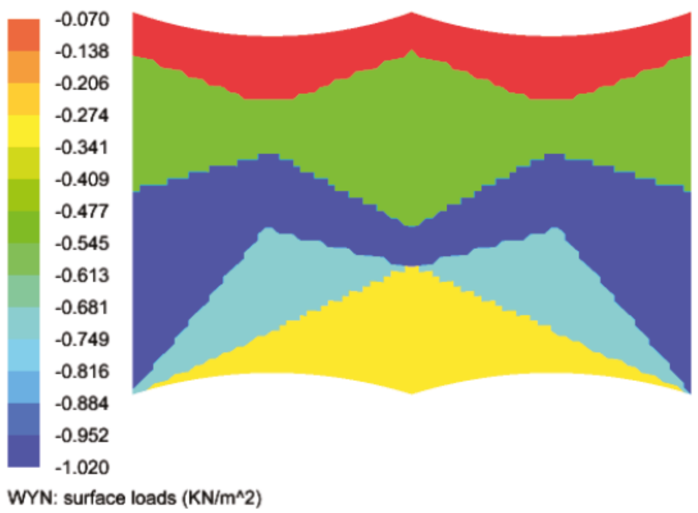
Wind flow from x direction (X+)



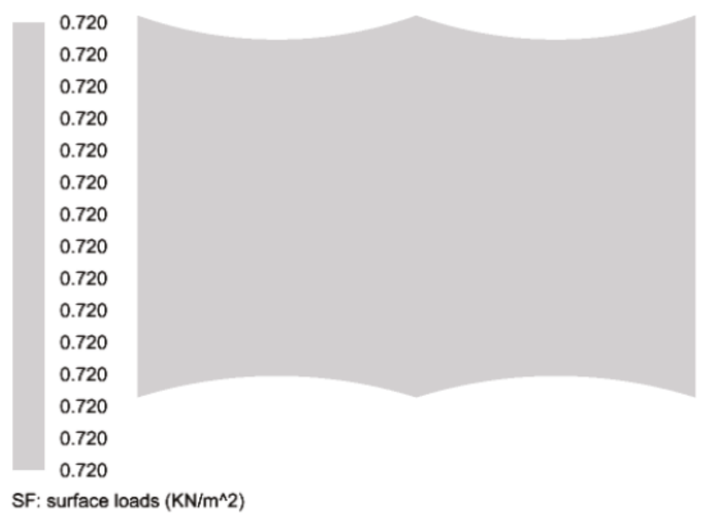
Wind flow from y direction (Y+)



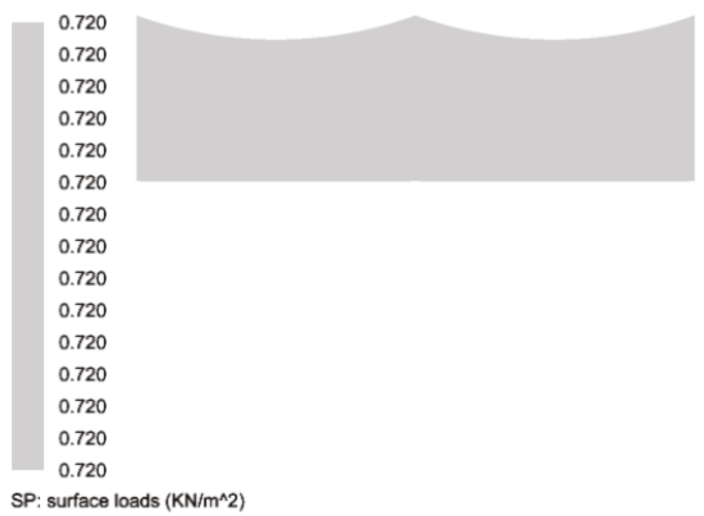
Wind flow from negative y direction (Y-)



Full snow load (FS)



Partial snow load (PS)



6.5 Structural analysis model

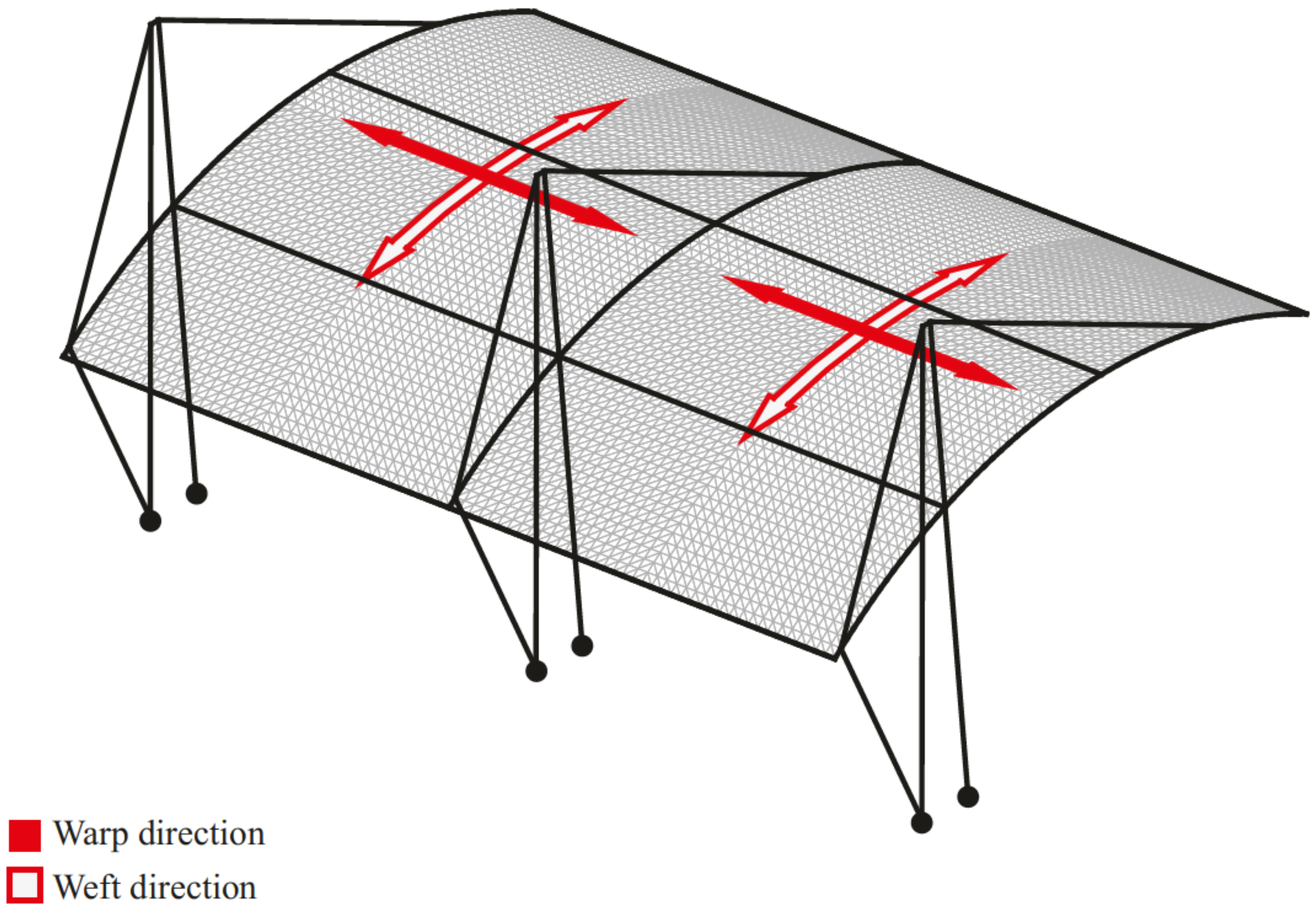


Figure 4.6 The ixCube nonlinear analysis initial model

The structural modelling process was completed.
All connection node are touching each other to transfer the loads. The material properties and profile cross sections were defined. The load combination was prepared to simulate the structural behavior under the external loads. The structure restrained with six point. The design is ready for form-finding and structural analysis process.

An intensive mesh was created in order to get more smooth surface and stress distribution. The mesh surface is consisting from in the warp direction 60, in the weft direction 40 segments.

Membrane structural properties

Type II PVC/PES

E module Warp	440 KN/m
E module Weft	440 KN/m
Poisson 12	0,5
Poisson 23	0,5
Thickness	0,001m
Density	0,0108 kN/m²

Steel structural properties

S235

E module	20600 kN/cm²
Poisson	0,2875
Density	76,98 kN/m³

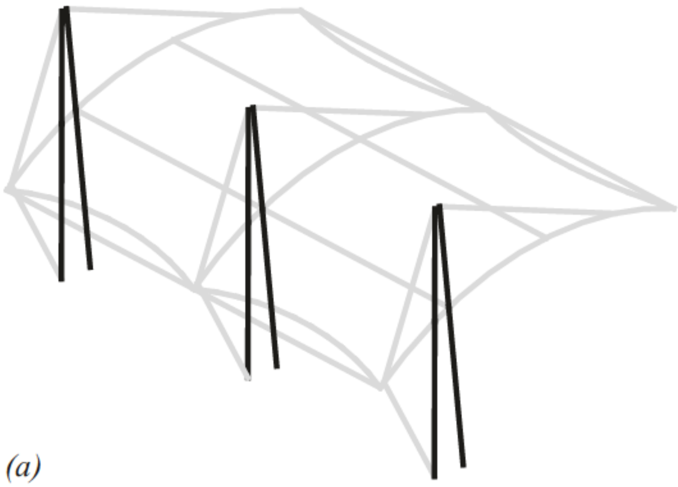
Steel cable structural properties

12mm

E module	16438 kN/cm²
Poisson	0,2875
Density	80,71 kN/m³

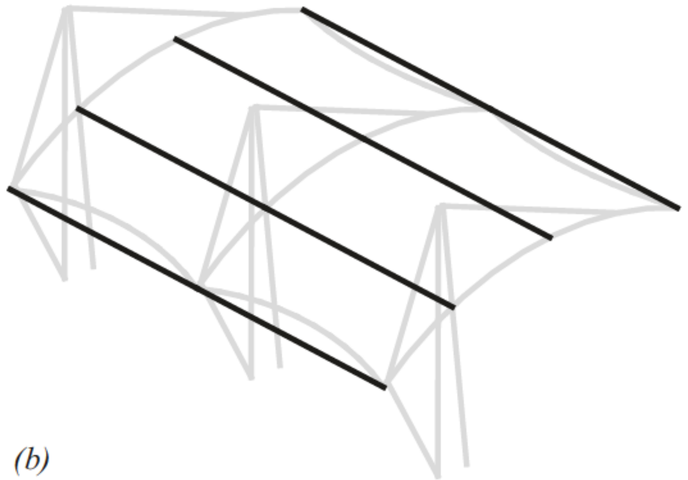
Note: The ixCube software has a large material and profile cross section library. The materials used in this project were selected from the ixCube library without modification. The material properties may need to be adjusted according to a specific project.

6.6 Structural analysis members



(a)

Section	CHS 139,7x6mm
Type	Beam
Behaviour	Nonlinear
Deformability	Stiff deformable
C Value	100

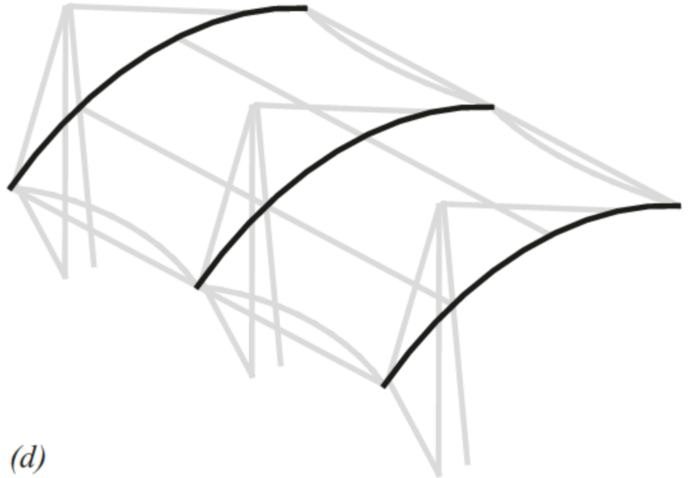


(b)

Section	CHS 114,3x5mm
Type	Beam
Behaviour	Nonlinear
Deformability	Stiff deformable
C Value	100

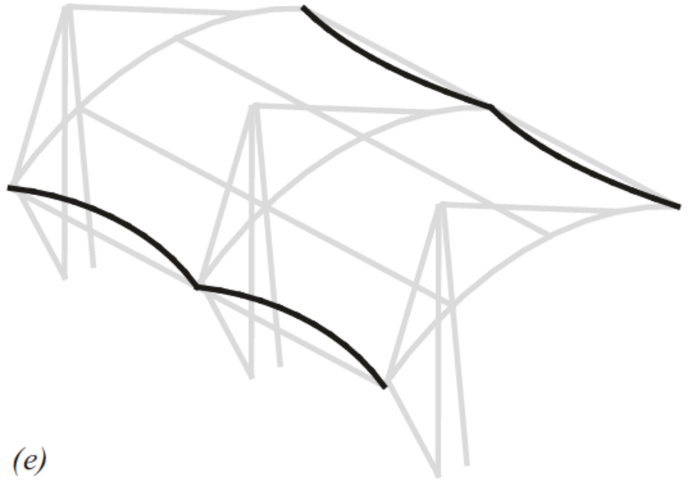
(c)

Section	CHS 48x5mm
Type	Truss
Behaviour	Nonlinear
Deformability	Stiff deformable
C Value	100



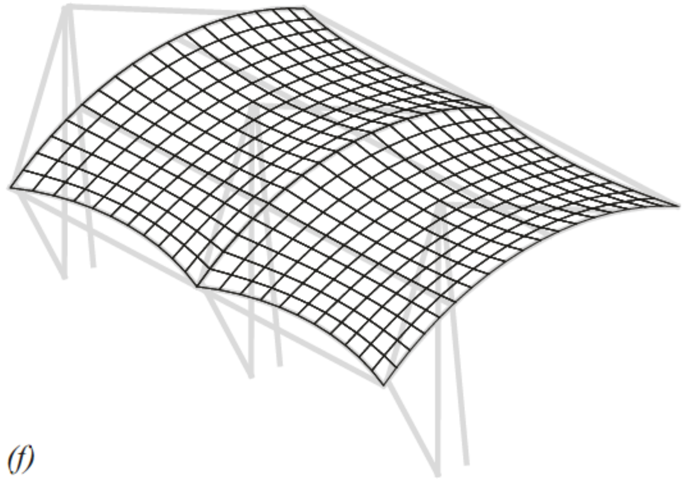
(d)

Section	CHS 139,7x6mm
Type	Beam
Behaviour	Nonlinear
Deformability	Stiff deformable
C Value	100



(e)

Section	12mm
Type	Cable
Behaviour	Nonlinear
Deformability	FF deformable
C Value	50



(f)

Section	Type II
Type	Membrane
Behaviour	Nonlinear
Deformability	FF deformable
C Value	Warp 1,25 Weft 1,25

Figure 4.7 The structural model members

6.7 Steel construction members analysis results

The most critical profile cross sections determined by the ixCube EC3 steel check plug-in

a) Strength check

Section	LC	Element ID	N(kN)	Vy(kN)	Vz(kN)	My(kN)	Mz(kN)
1	6	10147	-101,81	0,11	-6,68	-8,19	-0,13
2	9	10166	-18,15	2,83	0,47	-1,30	7,05
3	6	10156	64,47	-	-	-	-
4	6	Multi	-29,80	-14,16	1,82	3,30	-8,94

Table 4.6.a

b) Flexural buckling and moment check

Section	LC	Element ID	Ned(kN)	My,ed(kN)	Mz,ed(kN)
1	6	10146	-120,95	-3,01	-1,04
2	3	10164	-49,89	-0,11	1,58
3	3	10156	-19,5	-	-
4	6	Multi	-29,80	4,80	-8,94

Table 4.6.b

Note: The complete result of the analysis was attached to the thesis annex.

6.8 Anchor point reactions

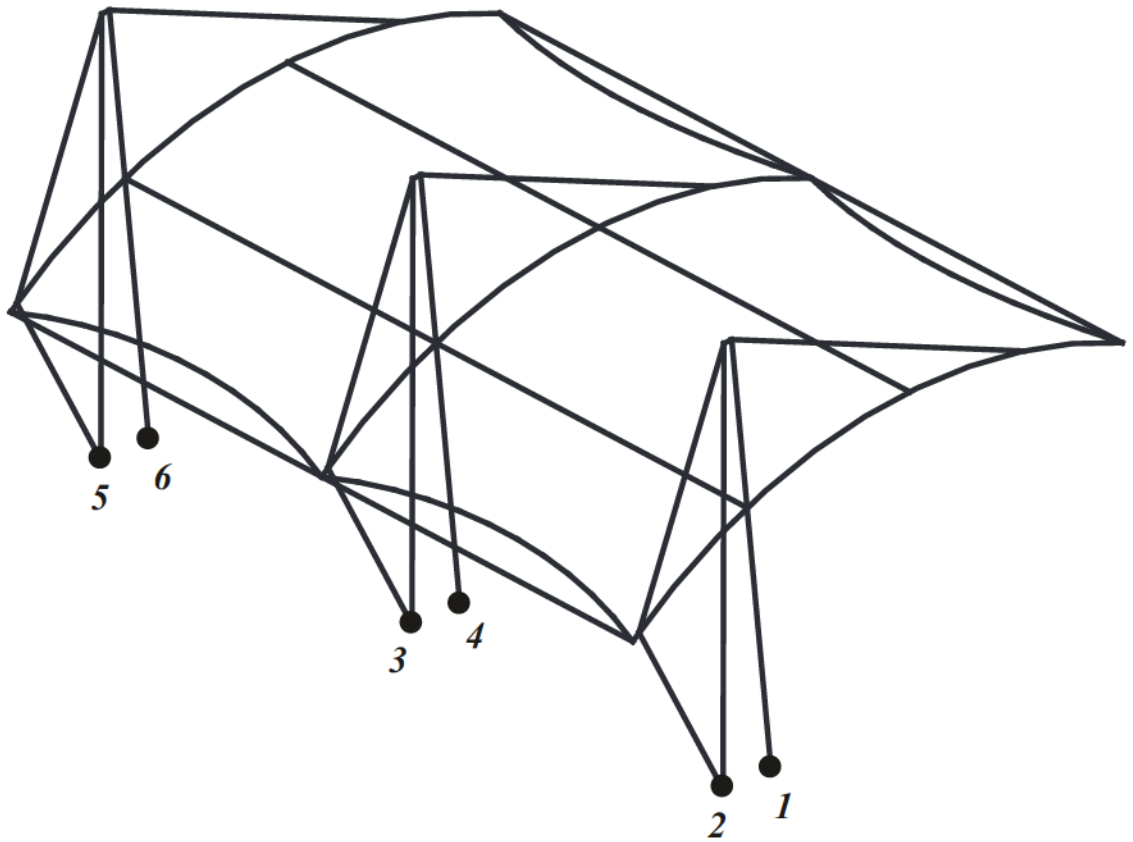


Figure 4.8

The structure was fully restrained by six anchor points. Table 4.7 shows anchor point reactions which are coming from most critical load combinations.

LC6 Resullts

N	Fx KN	Fy KN	Fz kN	Mx kNm	My kNm	Mz kNm	Fv kN
1	0.10	10.33	-83.44	-3.48	0.12	-0.06	84.08
2	-0.82	-6.98	57.21	-4.32	-1.31	-0.10	57.64
3	0.14	-14.67	68.02	-0.71	0.22	0.01	69.58
4	0.64	11.03	-120.88	1.45	1.03	0.12	121.38
5	0.95	-5.80	50.58	-4.10	1.53	0.11	50.92
6	0.55	9.38	-72.91	-3.62	0.95	0.17	73.52

Table 4.7.a

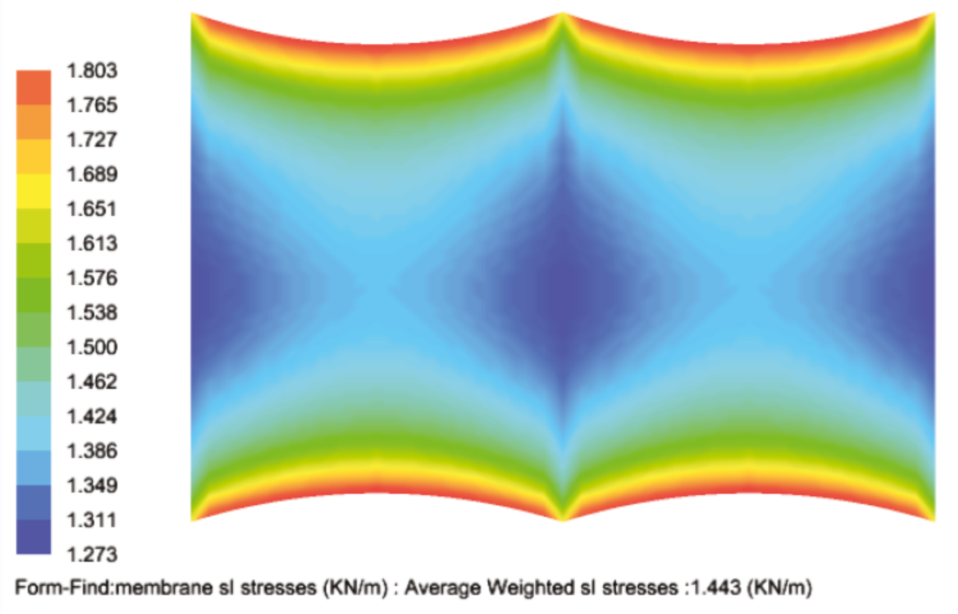
LC3 Resullts

N	Fx KN	Fy KN	Fz kN	Mx kNm	My kNm	Mz kNm	Fv kN
1	-1.06	-5.16	41.65	1.63	-1.71	-0.16	41.98
2	-0.77	-0.41	-32.70	6.15	-1.19	-0.09	32.71
3	0.00	3.15	-38.66	5.32	0.00	0.00	38.79
4	0.00	-4.85	54.44	-0.98	0.00	0.00	54.65
5	0.77	-0.44	-32.63	6.15	1.19	0.09	32.64
6	1.06	-5.15	41.59	1.63	1.71	0.16	41.92

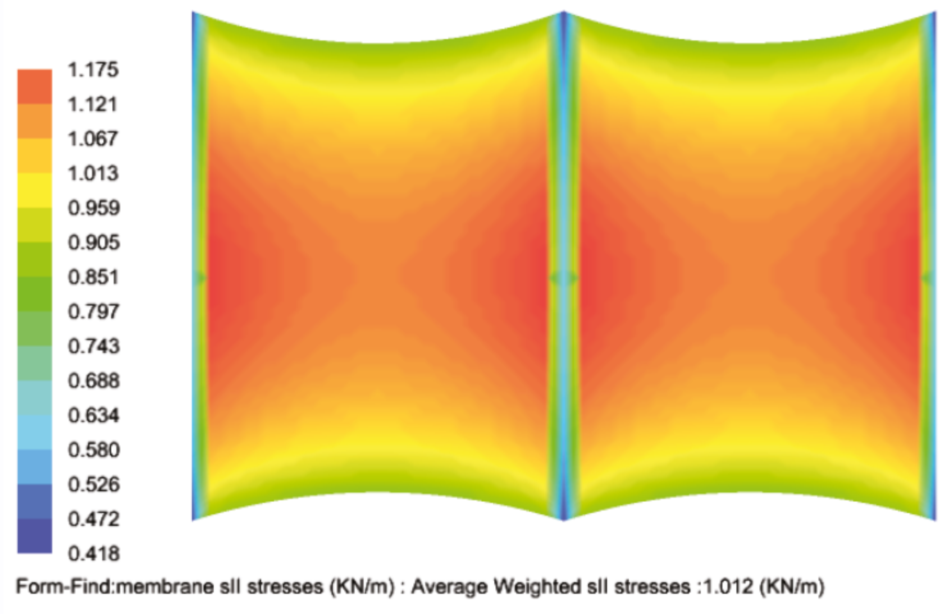
Table 4.7.b

6.9 Membrane form-finding stresses

Membrane warp stresses

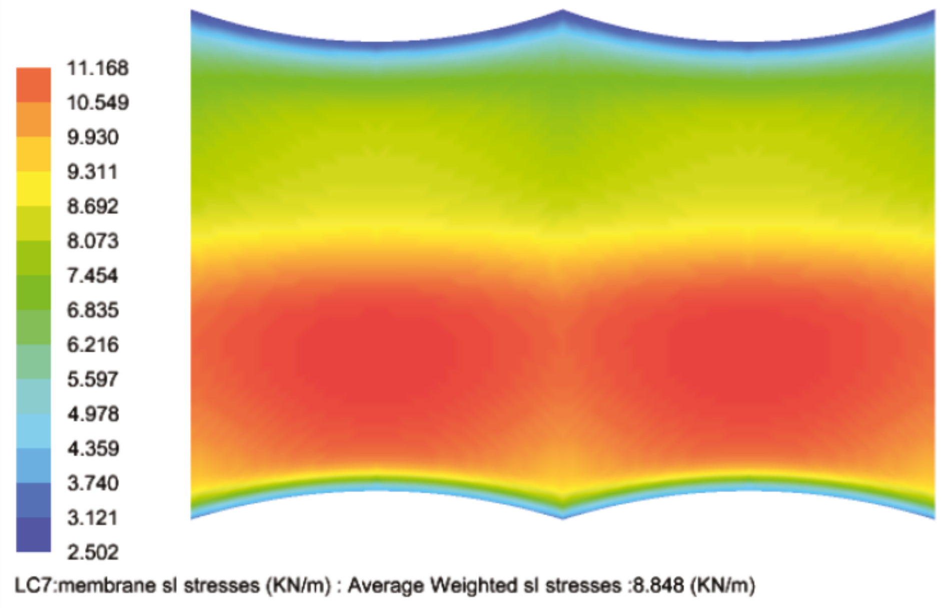


Membrane weft stresses

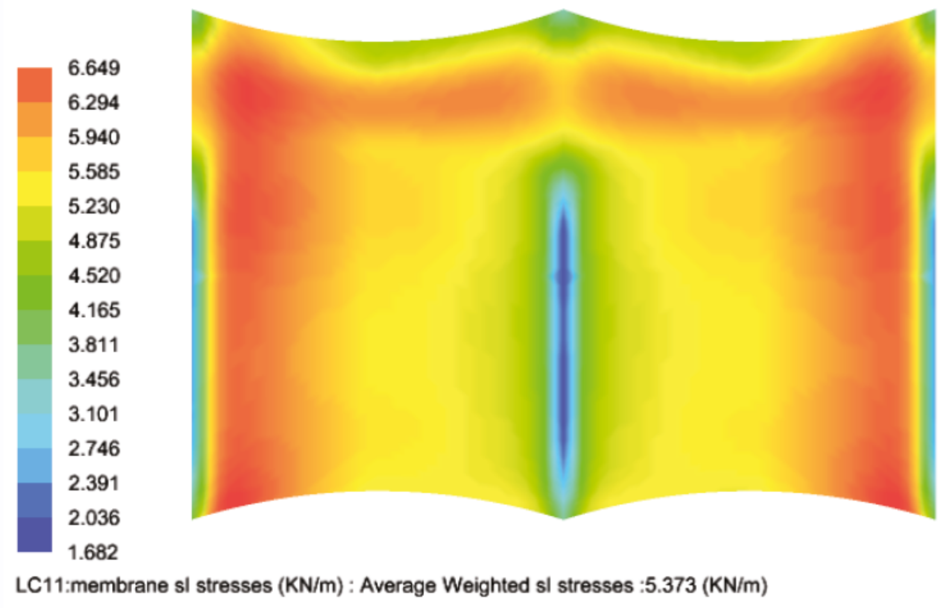


6.10 Membrane maximum stresses due to external loads

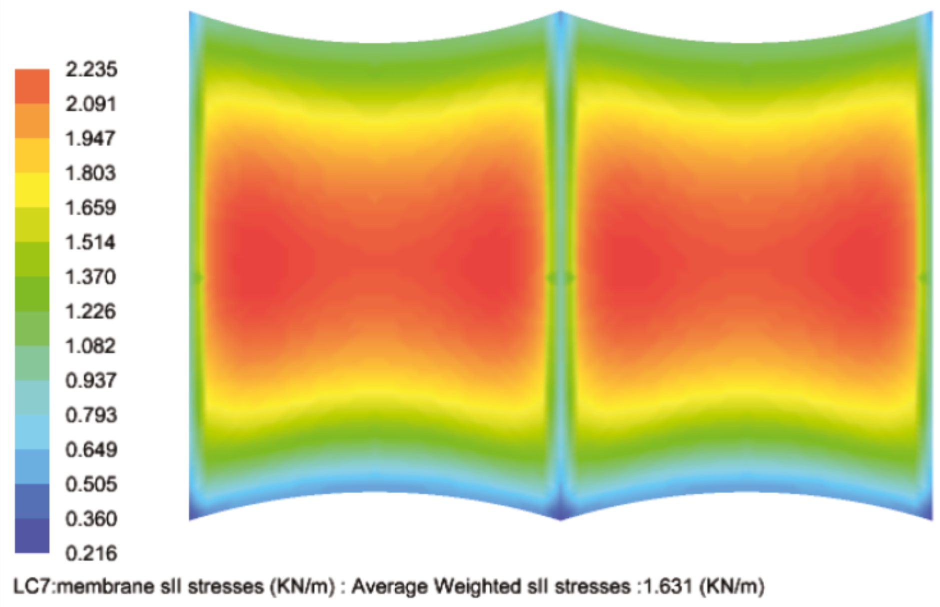
Membrane warp stresses due to LC7



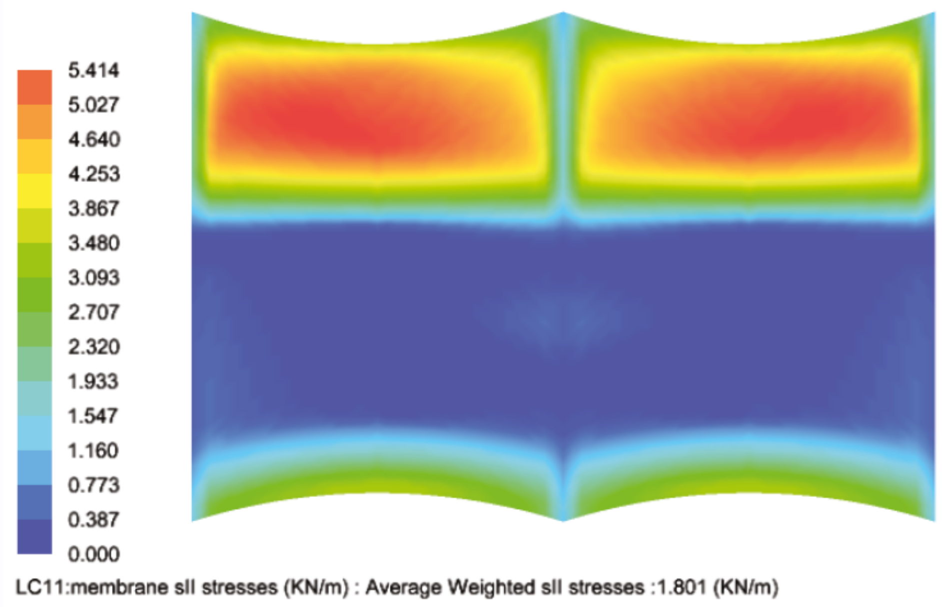
Membrane warp stresses due to LC11



Membrane weft stresses due to LC7



Membrane weft stresses due to LC11



6.11 Membrane stresses check

Membrane stresses checked according to the A Factor Method.

Membrane material

Membrane: Type II PVC/PES

Tensile strength: Warp direction $4400 N / 50mm$

Tensile strength: Weft direction $4000 N / 50mm$

$$f_d = \frac{f_k}{\gamma_m \cdot A_{res}} \geq n$$

f_d : Allowable stress

f_k : Tensile strength

γ_M : Material safety coefficient

$\gamma_{m,m}$: For fabric structure = 1.4

A_i : Reduction factors depending on load case

n : Actual membrane stress

Reduction factor for,

A_0 : Tensile test procedures of measuring biaxial strength

A_1 : Long-term loads

A_2 : Pollution and degradation

A_3 : High temperature load cases

Total reduction factors for the material depend on load case

	A_0	A_1	A_2	A_3	A_{res}
Permanent	1,2	1,7	1,2	1,25	3
Wind Storm	1,2	-	1,2	-	1,44
Max. Snow	1,2	1,7	1,2	-	2,45

Actual design stresses (n)

LC1	Permanent	Warp stresses	1.8 kN/m
LC1	Permanent	Weft stresses	1.18 kN/m
LC7	Max. snow	Warp stresses	1 1,17 kN/m
LC11	Max. snow	Weft stresses	5,41 kN/m

Ultimate tensile strength of the material

$Warp\ f_k = 88kN / m \qquad Weft\ f_k = 80kN / m$

-Permanent allowable stress in the warp direction

$$f_d = \frac{f_k}{\gamma_m \times A_{res}} = \frac{88}{1,4 \times 3} = 21kN / m \quad \geq 1,8$$

-Permanent allowable stress in the weft direction

$$f_d = \frac{f_k}{\gamma_m \times A_{res}} = \frac{80}{1,4 \times 3} = 19kN / m \quad \geq 1,18$$

-Max. snow allowable stress in the warp direction

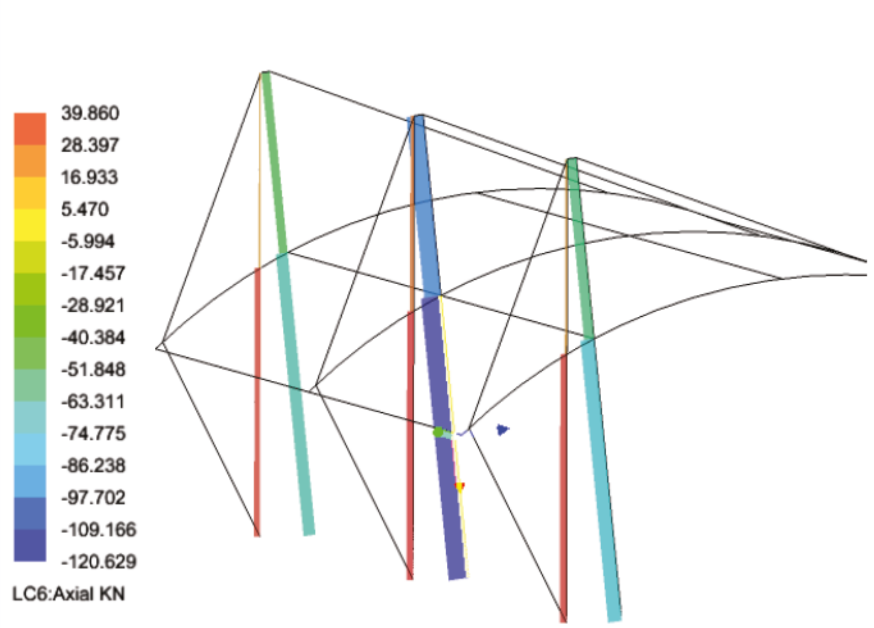
$$f_d = \frac{f_k}{\gamma_m \times A_{res}} = \frac{88}{1,4 \times 2,45} = 26kN / m \quad \geq 11,17$$

-Max. snow allowable stress in the weft direction

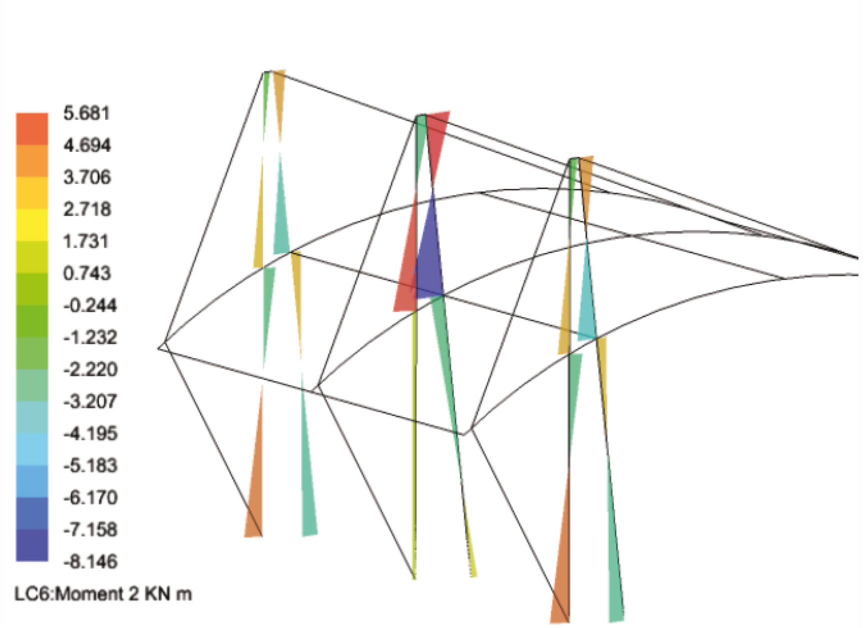
$$f_d = \frac{f_k}{\gamma_m \times A_{res}} = \frac{80}{1,4 \times 2,45} = 23kN / m \geq 5,41$$

6.12.1 Mast (p1) reactions

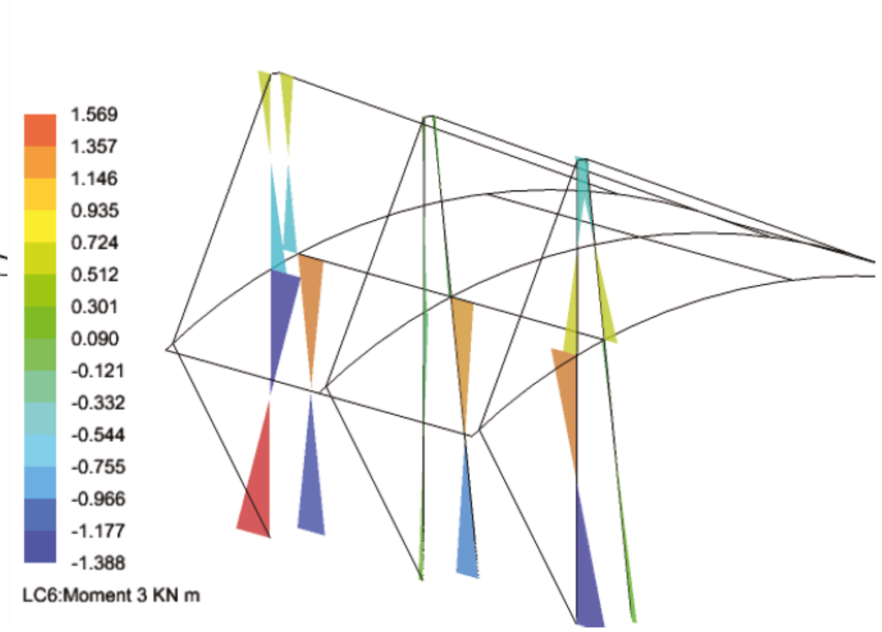
LC6 - Mast axial reactions



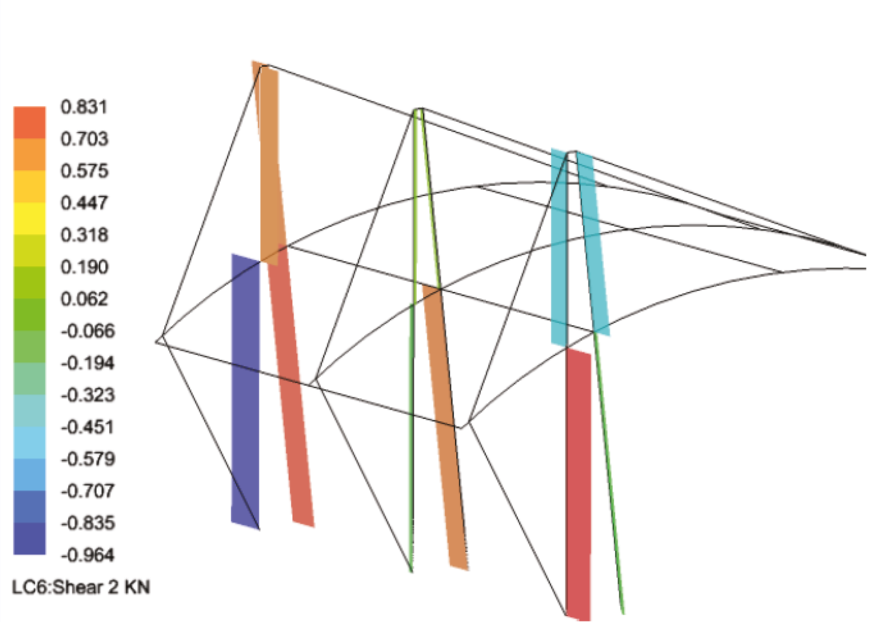
LC6 - Mast M2 reactions



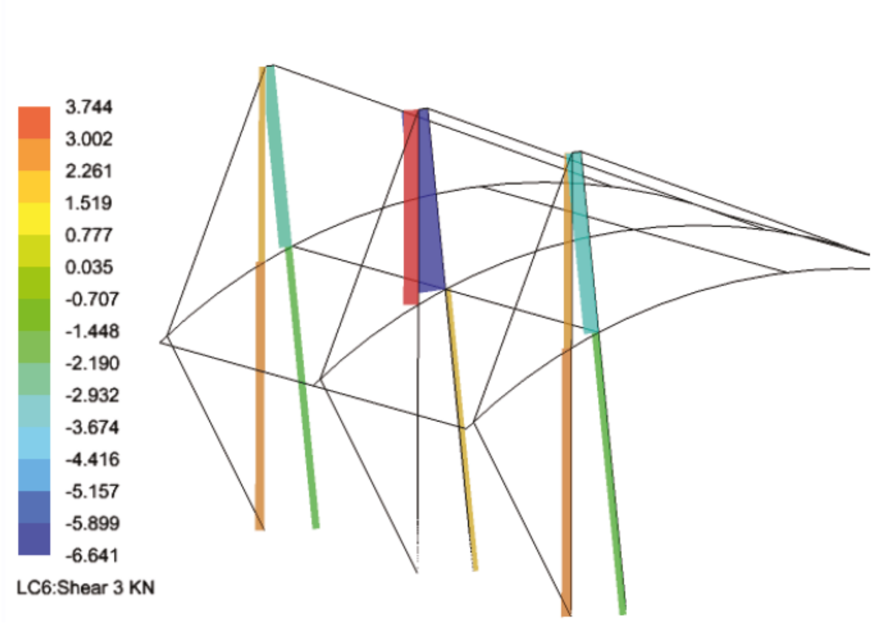
LC6 - Mast M3 reactions



LC6 - Mast shear 2 reactions

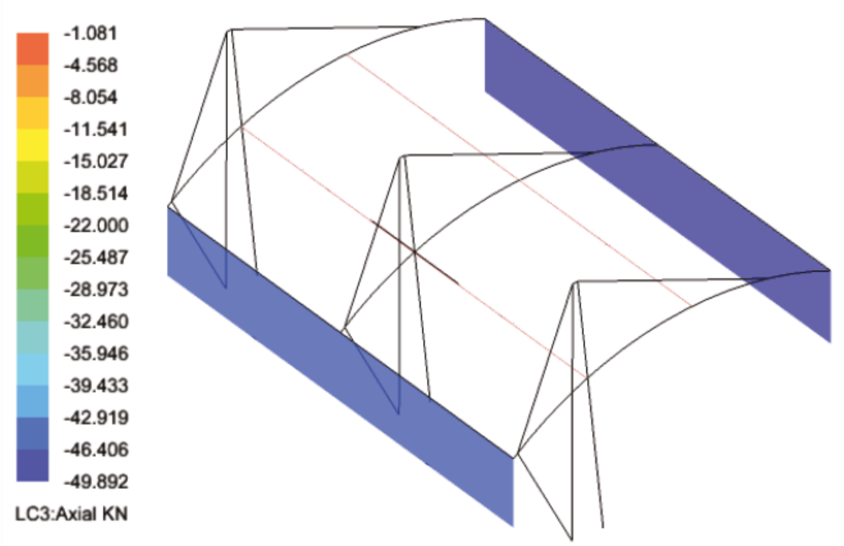


LC6 - Mast shear 3 reactions

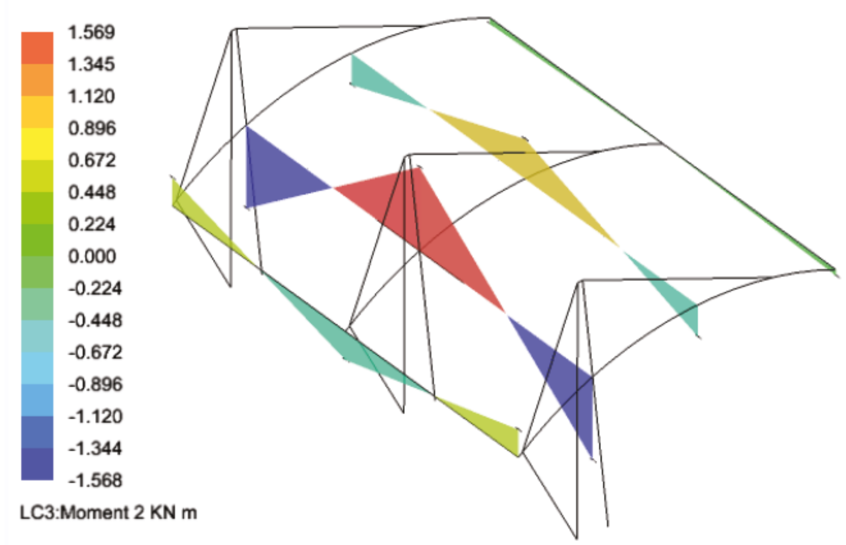


6.12.2 Compression beam (p2) reactions

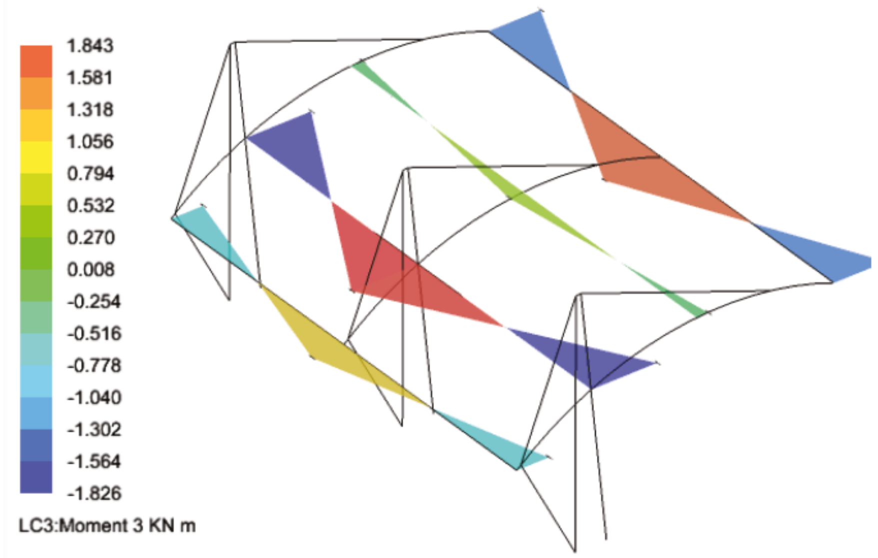
LC3 - Connection beam axial reactions



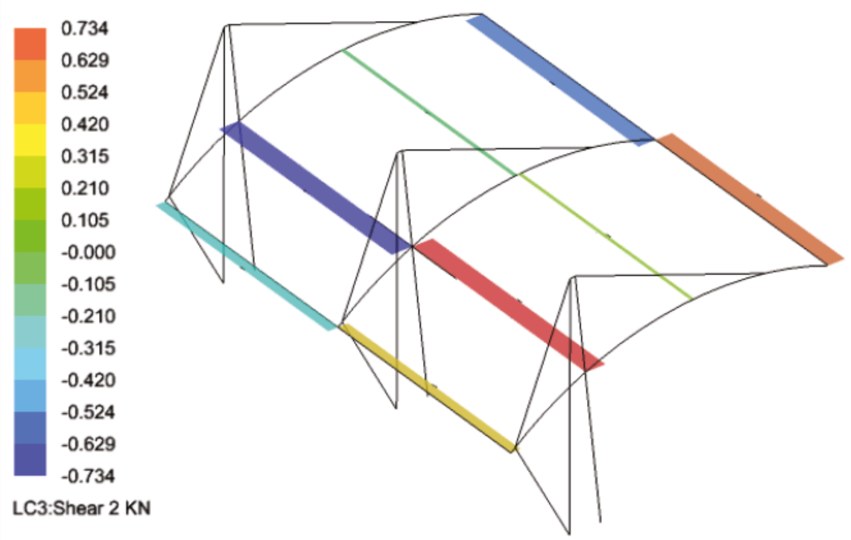
LC3 - Connection beam M2 reactions



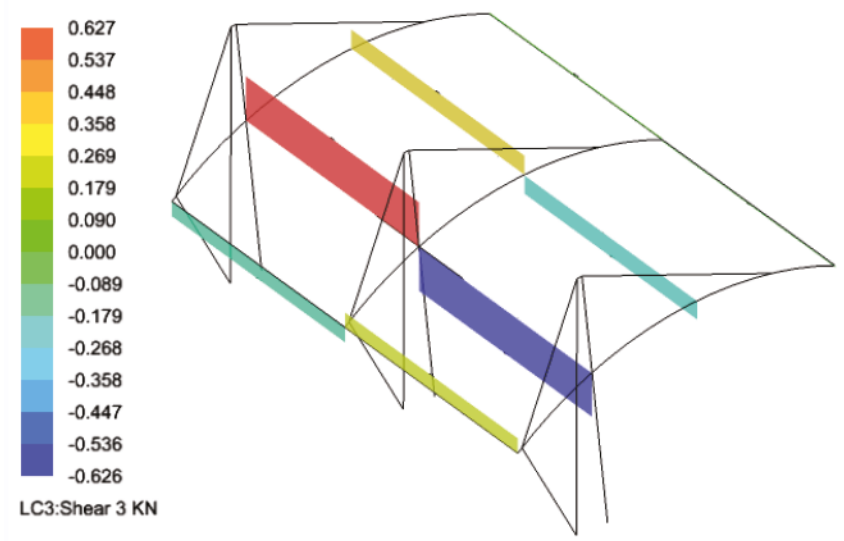
LC3 - Connection beam M3 reactions



LC3 - Connection beam shear 2 reactions

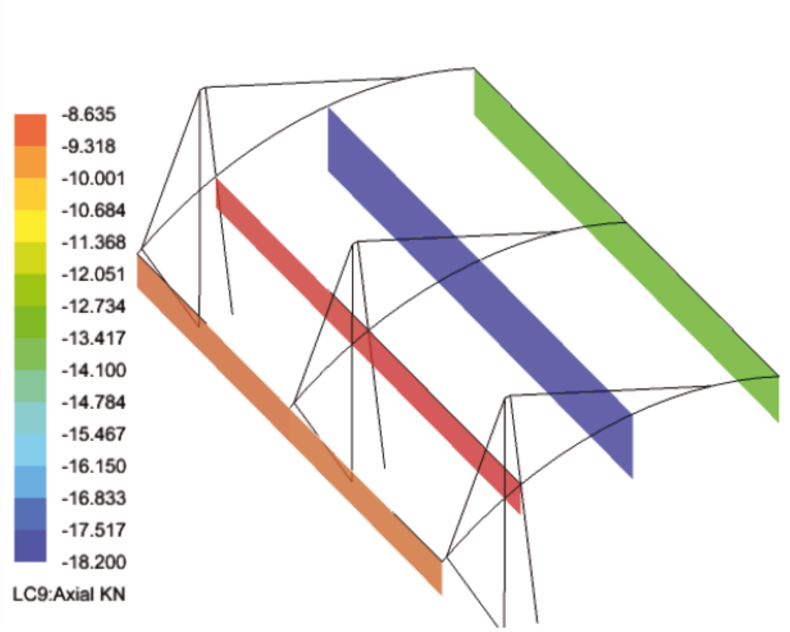


LC3 - Connection beam shear 3 reactions

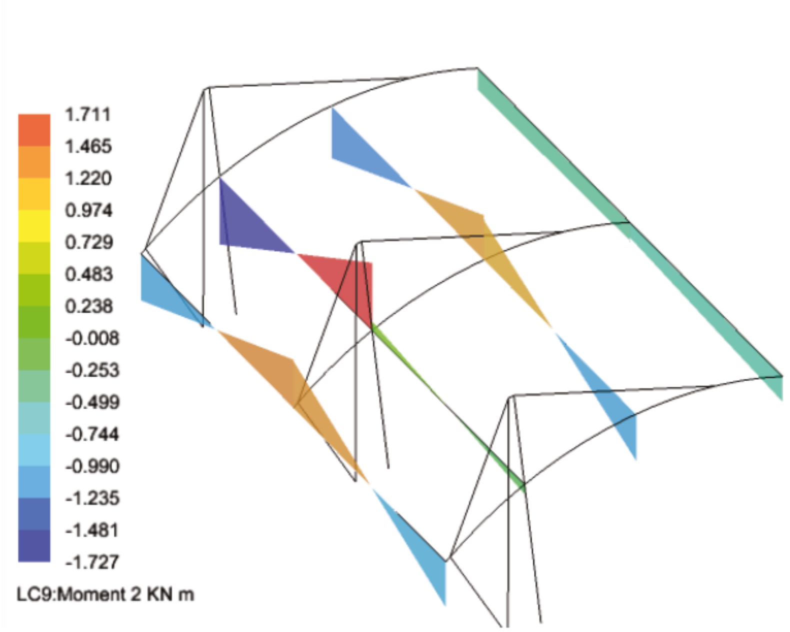


6.12.3 Compression beam (p2) reactions

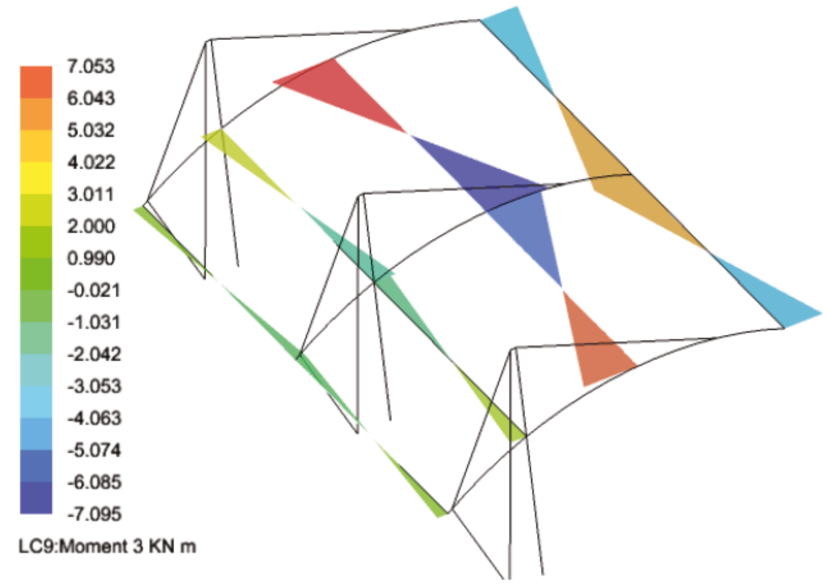
LC9 - Connection beam axial reactions



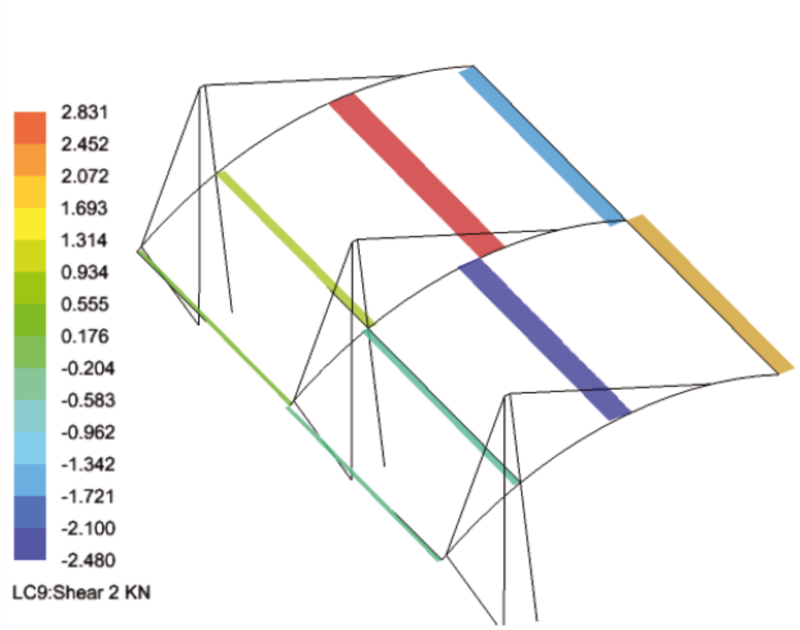
LC9 - Connection beam M2 reactions



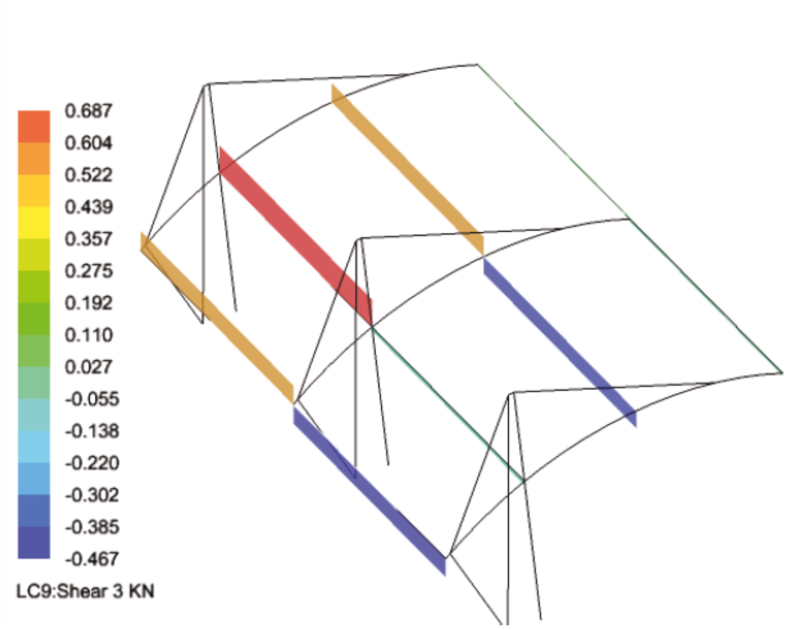
LC9 - Connection beam M3 reactions



LC9 - Connection beam shear 2 reactions

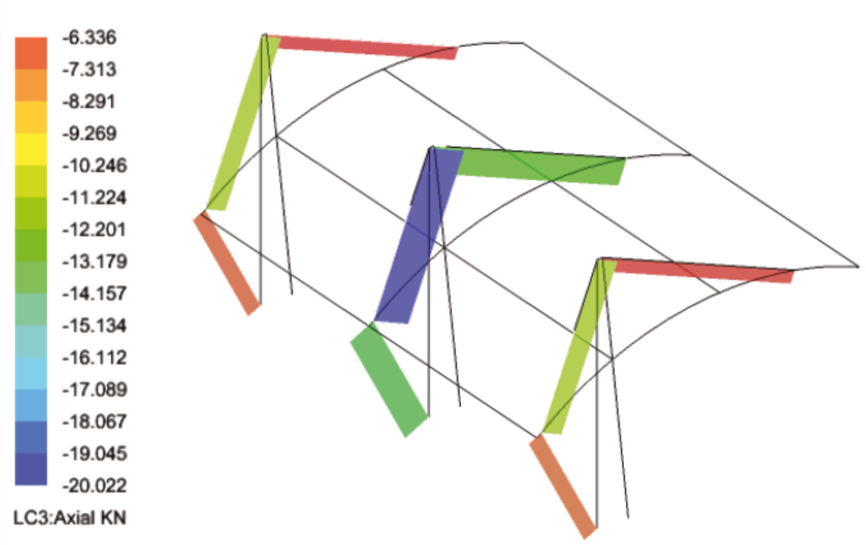


LC9 - Connection beam shear 3 reactions

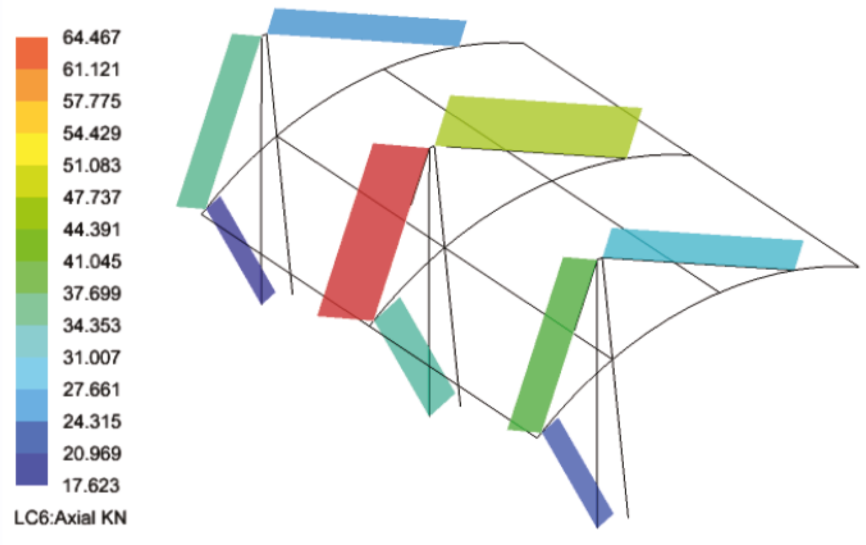


6.12.4 Suspension truss (p3) reactions

LC3 - Suspension truss axial reaction

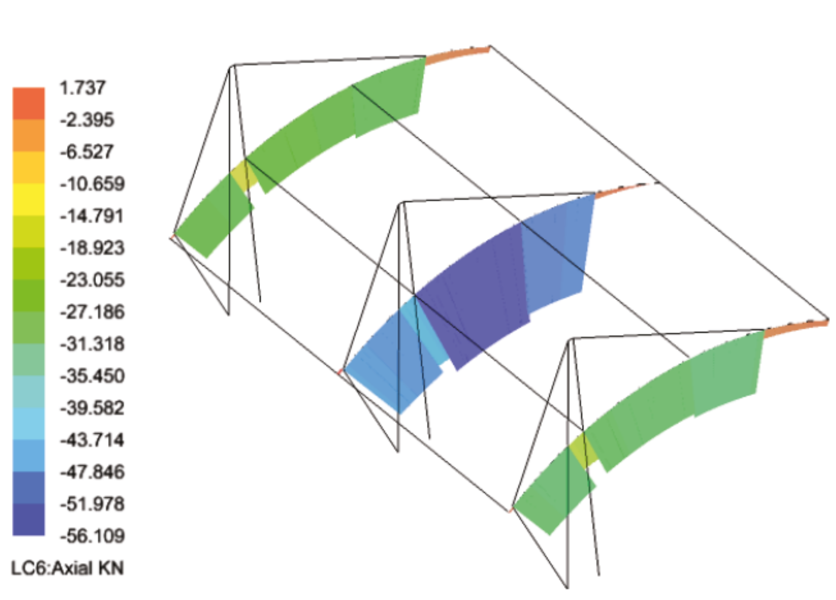


LC6 - Suspension truss axial reaction

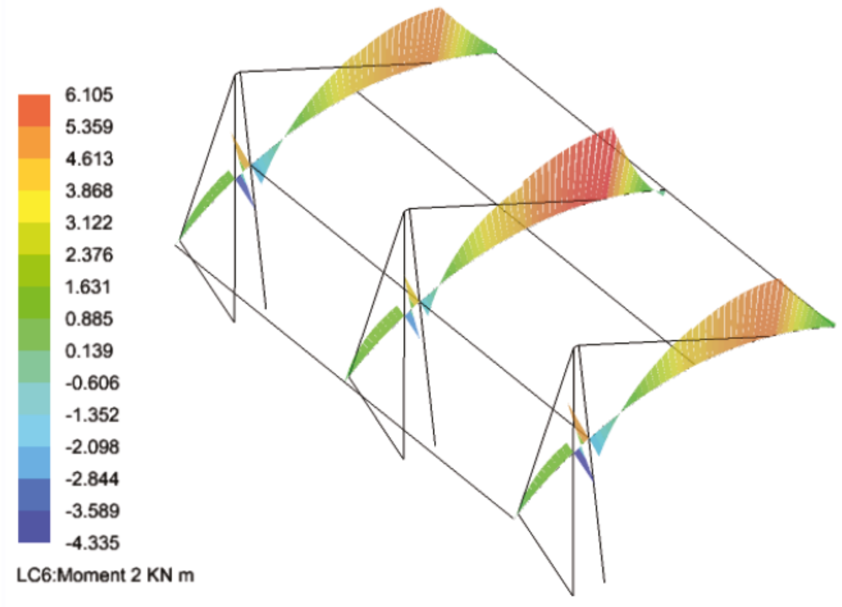


6.12.5 Arch beam (p4) reactions

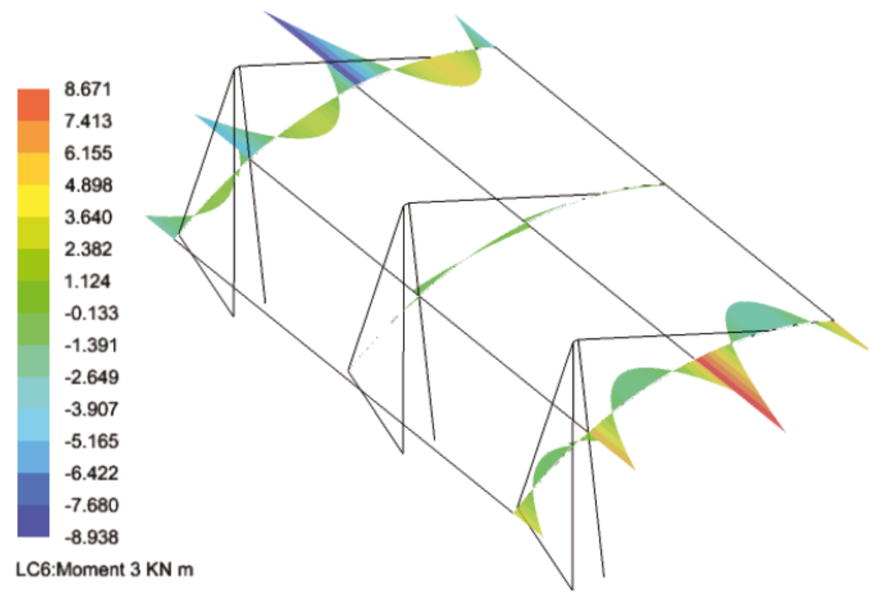
LC6 - Arch axial reactions



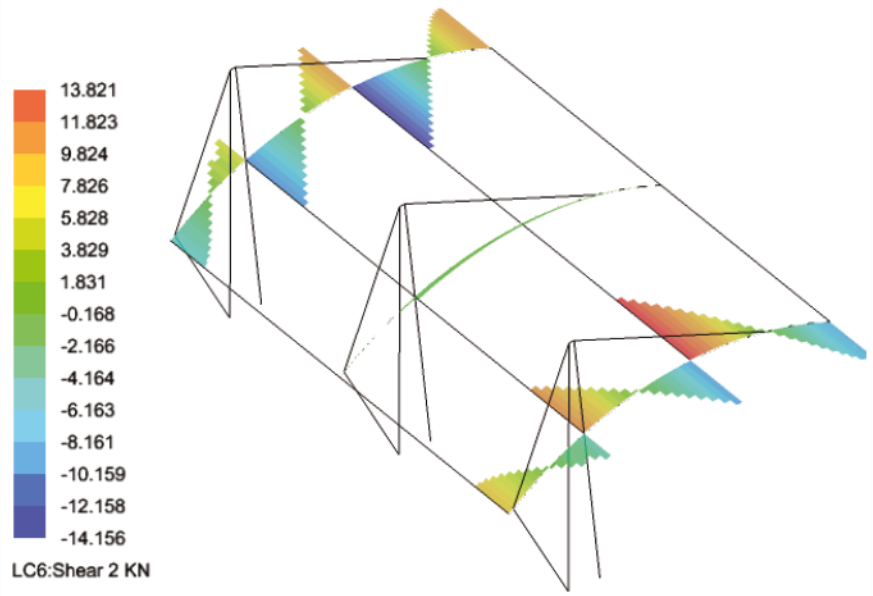
LC6 - Arch M2 reactions



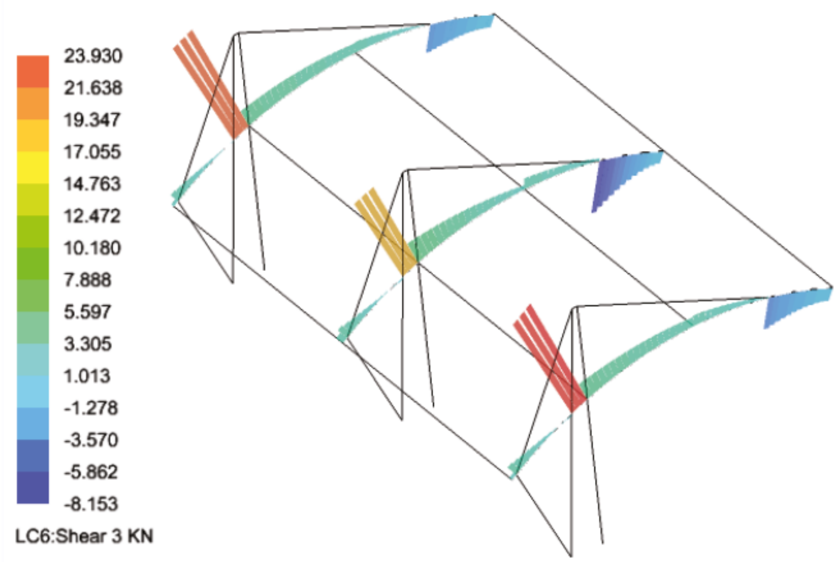
LC6 - Arch M3 reactions



LC6 - Arch shear 2 reactions

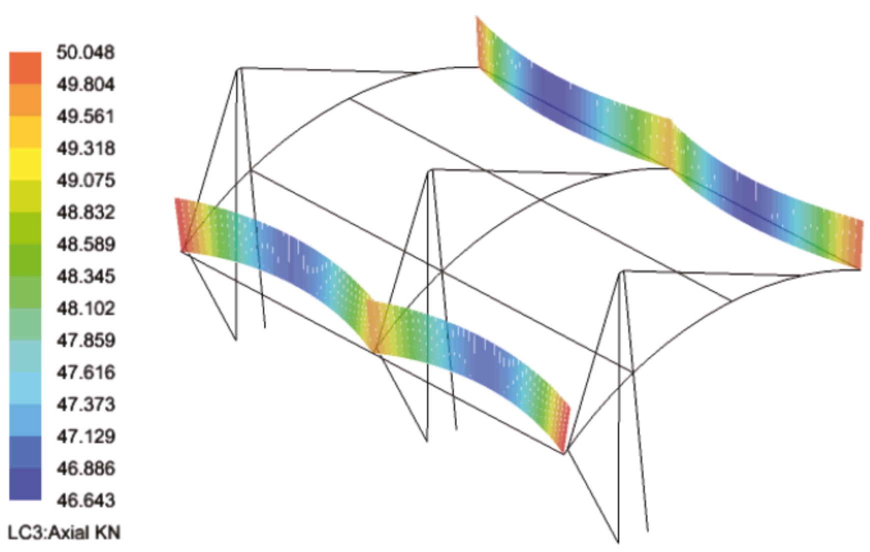


LC6 - Arch shear 3 reactions

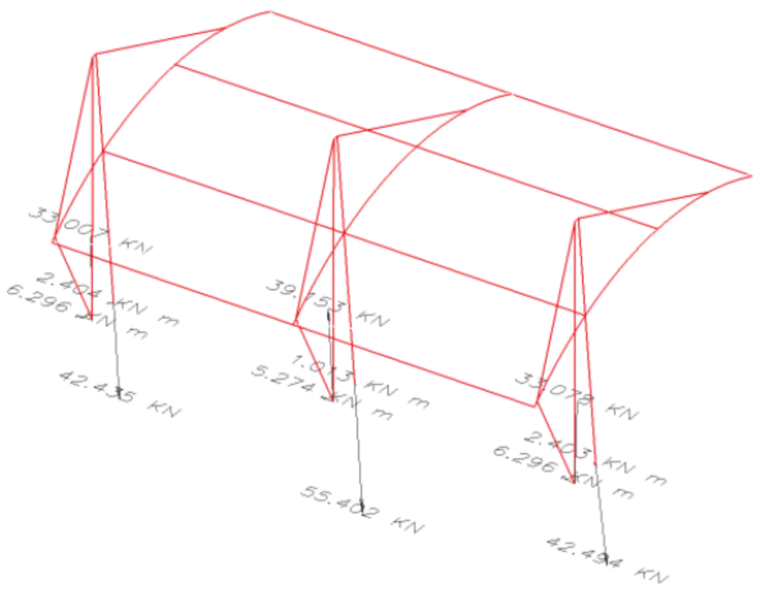


6.12.6 Border cable and anchor point reactions

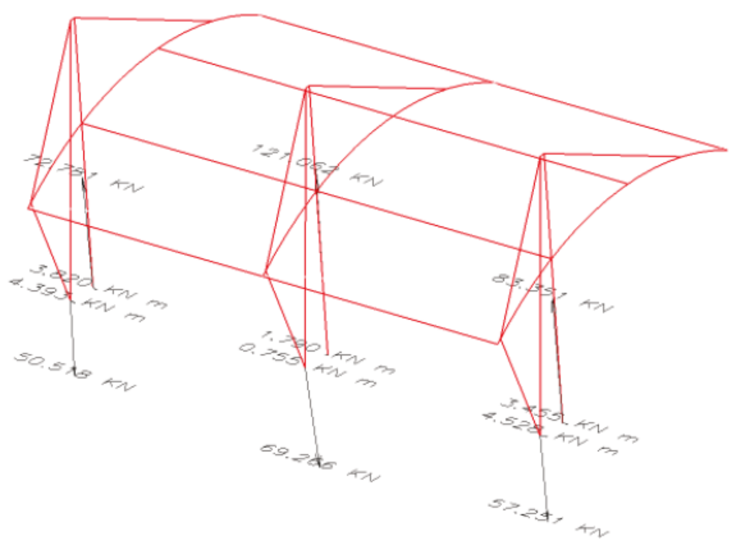
LC3 - Border cable axial reaction



LC3 - Anchor point reactions

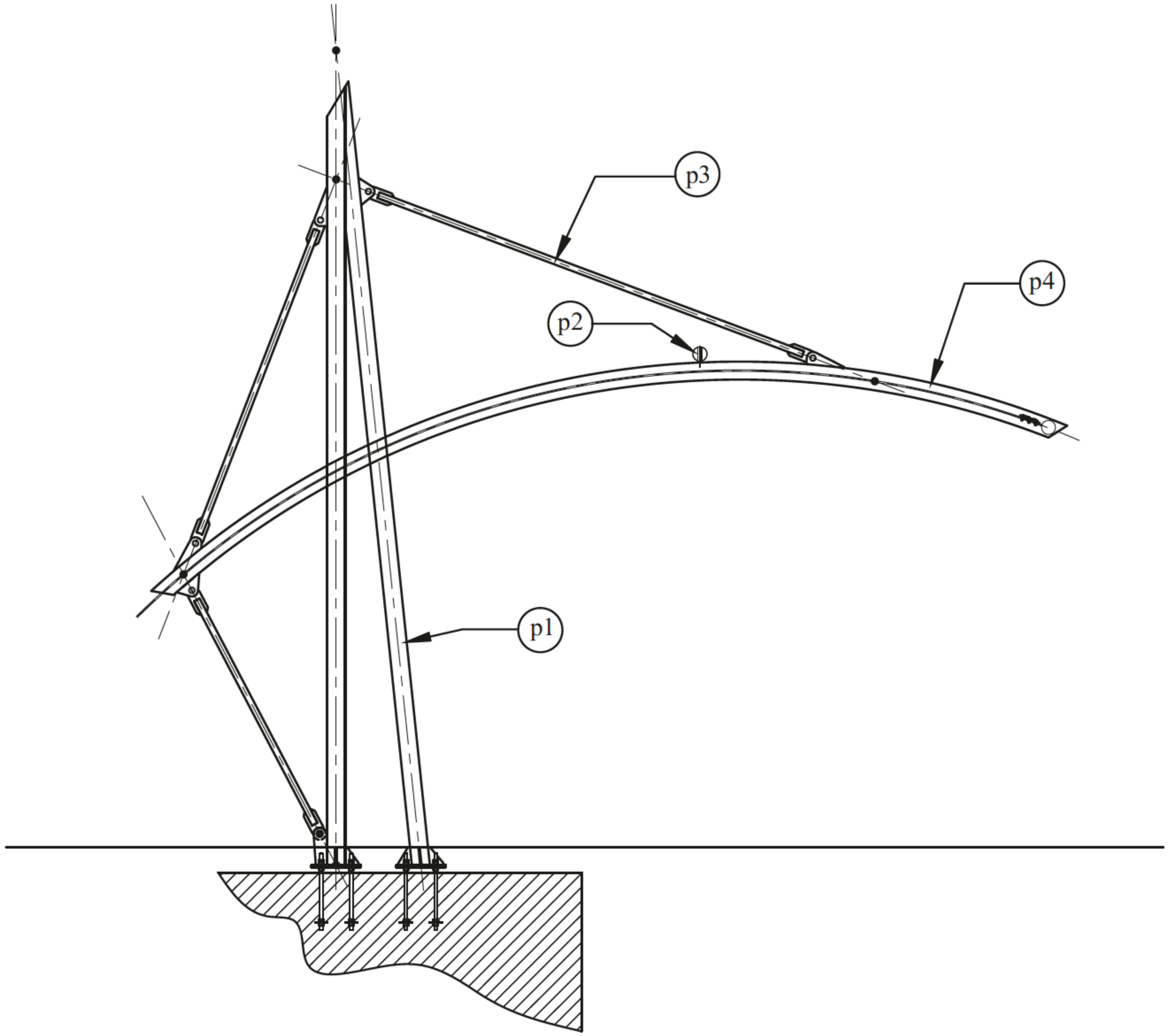


LC6 - Anchor point reactions



7. Construction members cross section check

The construction is consisting of four type elements. The cross sectional adequacy of these elements was checked according to EN 1993-1-1.



7.1 Mast (p1) check

CHS139,7x6

Element ID: 10147 LC6

$N_{Ed} : -101,31kN \quad M_{y,Ed} : -8,15kNm \quad M_{z,Ed} : -0,12kNm$

$V_{y,Ed} : 0,11kN \quad V_{z,Ed} : -6,64kN$

$A : 25,20cm^2 \quad I_{yy,zz} : 564,26cm^4 \quad W_{pl,y,z} : 107,33cm^3$

$f_y : 235N/mm^2 \quad f_u : 360N/mm^2 \quad t \leq 40mm$

$E : 210000N/mm^2$

Cross section classification

$$\varepsilon = \sqrt{\frac{235}{f_y}} \rightarrow \sqrt{\frac{235}{235}} = 1$$

$$\frac{d}{t} \cdot \varepsilon^2 \leq 50 \cdot \varepsilon^2 \rightarrow \frac{13,97}{0,6} \cdot 1^2 \leq 50 \cdot 1 \quad \text{section class 1}$$

Compression check

$$\frac{N_{Ed}}{N_{c,Rd}} \leq 1,0$$

$$N_{c,Rd} = \frac{A \cdot f_y}{\gamma_{M0}} \rightarrow \frac{25,20 \cdot 23,5}{1,05} = 564kN$$

$$\frac{N_{Ed}}{N_{c,Rd}} \rightarrow \frac{101,3}{564} = 0,18 \leq 1$$

Shear check

$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1,0$$

$$A_v = \frac{2 \cdot A}{\pi} \rightarrow \frac{2 \cdot 25,20}{\pi} = 16,04cm^2$$

$$V_{c\,Rd} = \frac{A_v \cdot \left(\frac{f_y}{\sqrt{3}}\right)}{\gamma_{M0}} \rightarrow \frac{16,04 \cdot \left(\frac{23,5}{\sqrt{3}}\right)}{1,05} = 207,26kN$$

$$\frac{V_{Ed}}{V_{c,Rd}} \rightarrow \frac{6,64}{207,26} = 0,03 \leq 1$$

Bending moment check

$$\frac{M_{Ed}}{M_{c,Rd}} \leq 1,0$$

$$M_{c,Rd} = \frac{W_{pl} \cdot f_y}{\gamma_{M0}} \rightarrow \frac{107,33 \cdot 23,5}{1,05} = 2402kNcm \rightarrow 24,02kNm$$

$$\frac{M_{Ed}}{M_{c,Rd}} \rightarrow \frac{8,15}{24,02} = 0,34 \leq 1$$

Combined axial force and bending moment check

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rd}} + \frac{M_{z,Ed}}{M_{z,Rd}} \leq 1 \rightarrow$$

$$\frac{101,31}{564} + \frac{8,15}{24,02} + \frac{0,12}{24,02} = 0,524 \leq 1$$

Element ID: 10146 LC6

Flexural buckling check

L: 325cm k:1

N_{Ed} : $-120,63kN$

$$N_{cr} = \frac{\pi^2 \cdot E \cdot I_{y,z}}{L_c^2} \rightarrow \frac{\pi^2 \cdot 21000 \cdot 564,26}{325^2} = 1107,214$$

Non– dimensional slenderness

$$\bar{\lambda}_{y,z} = \sqrt{\frac{A \cdot f_y}{N_{cr}}} \rightarrow \sqrt{\frac{25,20 \cdot 23,5}{1107,214}} = 0,731$$

Buckling curve c $\rightarrow$ imperfection factor α : 0,49

$$\phi = 0,5 \cdot \left(1 + \alpha\left(\bar{\lambda} - 0,2\right) + \bar{\lambda}^2\right) \rightarrow$$

$$0,5 \cdot \left(1 + 0,49 \cdot (0,731 - 0,2) + 0,731^2\right) = 0,897$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \; but \; \chi \leq 1 \quad \rightarrow \frac{1}{0,897 + \sqrt{0,897^2 - 0,731^2}} = 0,706$$

Design buckling resistance

$$N_{b,Rd} = \frac{\chi \cdot A \cdot f_y}{\gamma_{M1}} \rightarrow \frac{0,706 \cdot 25,20 \cdot 23,5}{1,05} = 398,184kN$$

$$\frac{N_{Ed}}{N_{b,Rd}} = \frac{120,63}{398,184} = 0,303 \leq 1$$

Combined bending moment and compression check

$M2$: -3,01 - 1,46kNm

$M3$: 1,04 - -1,04kNm

$\bar{\lambda}_{y,z} = 0,731 \quad \chi_{y,z} = 0,706$

$$M_{Rk} = W_{pl} \cdot f_y \rightarrow 107,33 \cdot 23,5 = 2522,25kNcm \rightarrow 25,22kNm$$

$$N_{Rk} = A \cdot f_y \rightarrow 25,20 \cdot 23,5kN / cm^2 = 592,2kN$$

$\chi_{LT} = 1$

$$C_{my} = 0.406 \quad \rightarrow \quad (0,6 + 0,4 \cdot \psi) \geq 0,4 \quad \psi = \frac{1,46}{-3,01} = -0,485$$

$$\rightarrow (0,6 + 0,4 \cdot (-0,485)) = 0,406$$

$$C_{m<} = 0.4 \quad \rightarrow \quad (0,6 + 0,4 \cdot \psi) \geq 0,4 \quad \psi = \frac{1,04}{-1,04} = -1$$

$$\rightarrow (0,6 + 0,4 \cdot (-1)) = 0,2$$

$$K_{yy} = C_{my} \cdot \left(1 + \left(\bar{\lambda}_y - 0.2\right) \cdot \frac{N_{Ed}}{\chi_y \cdot N_{Rk} / \gamma_{M1}}\right) \leq C_{my} \cdot \left(1 + 0,8 \cdot \frac{N_{Ed}}{\chi_y \cdot N_{Rk} / \gamma_{M1}}\right) \rightarrow$$

$$0.406 \cdot \left(1 + (0,731 - 0.2) \cdot \frac{120,63}{0,706 \cdot 592,2 / 1.05}\right) = 0,471 \leq 0,406.\left(1 + 0,8.\frac{120,63}{0,706 \cdot 592,2 / 1.05}\right) = 0,504 \rightarrow K_{yy} = 0,471$$

$$K_{zz} = C_{mz} \cdot \left(1 + \left(\bar{\lambda}_y - 0.2\right) \cdot \frac{N_{Ed}}{\chi_z \cdot N_{Rk} / \gamma_{M1}}\right) \leq C_{my} \cdot \left(1 + 0,8 \cdot \frac{N_{Ed}}{\chi_z \cdot N_{Rk} / \gamma_{M1}}\right) \rightarrow$$

$$0.4 \cdot \left(1 + (0,731 - 0.2) \cdot \frac{120,63}{0,706 \cdot 592,2 / 1.05}\right) = 0,464 \leq 0,4.\left(1 + 0,8.\frac{120,63}{0,706 \cdot 592,2 / 1.05}\right) = 0,497 \rightarrow K_{zz} = 0,464$$

$$K_{zy,} = 0,6 \cdot K_{yy} \rightarrow 0,6 \cdot 0,471 = 0,283 \qquad K_{yz} = 0,6 \cdot K_{zz} \rightarrow 0,6 \cdot 0,464 = 0,278$$

$$\frac{N_{Ed}}{\chi_y \cdot N_{xx} / \gamma_{M1}} + K_{yy} \cdot \frac{M_{Ed}}{\chi_{LT} \cdot M_{y,Rk} / \gamma_{M1}} + K_{yz} \cdot \frac{M_{z,Ed}}{\chi_{LT} \cdot M_{z,Rk} / \gamma_{M1}} \leq 1 \rightarrow \frac{120,63}{0.706 \cdot 592,2 / 1,05} + 0,471 \cdot \frac{3,01}{1 \cdot 25,22 / 1,05} + 0,278 \cdot \frac{1,04}{1 \cdot 25,22 / 1,05} = 0,374 \leq 1$$

$$\frac{N_{Ed}}{\chi_z \cdot N_{xx} / \gamma_{M1}} + K_{zy} \cdot \frac{M_{Ed}}{\chi_{LT} \cdot M_{y,Rk} / \gamma_{M1}} + K_{zz} \cdot \frac{M_{z,Ed}}{\chi_{LT} \cdot M_{z,Rk} / \gamma_{M1}} \leq 1 \rightarrow \frac{120,63}{0.706 \cdot 592,2 / 1,05} + 0,283 \cdot \frac{3,01}{1 \cdot 25,22 / 1,05} + 0,464 \cdot \frac{1,04}{1 \cdot 25,22 / 1,05} = 0,359 \leq 1$$

7.2 Compression beam (p2) check

CHS 114,3x5

Element ID: 10166 LC9

$N_{Ed} : -18,15kN \quad M_{y,Ed} : -1,31kNm \quad M_{z,Ed} : 7,05kNm$

$V_{y,Ed} : 2,83kN \quad V_{z,Ed} : 0,47kN$

$A : 17,17cm^2 \quad I_{yy,zz} : 256,92cm^4 \quad W_{pl,y,z} : 59,77cm^3$

$f_y : 235N/mm^2 \quad f_u : 360N/mm^2 \quad t \leq 40mm$

$E : 210000N/mm^2$

Cross section classification

$$\varepsilon = \sqrt{\frac{235}{f_y}} \rightarrow \sqrt{\frac{235}{235}} = 1$$

$$\frac{d}{t} \cdot \varepsilon^2 \leq 50 \cdot \varepsilon^2 \rightarrow \frac{11,4}{0,5} \cdot 1^2 \leq 50 \cdot 1 \quad \text{section class 1}$$

Compression check

$$\frac{N_{Ed}}{N_{c,Rd}} \leq 1,0$$

$$N_{c,Rd} = \frac{A \cdot f_y}{\gamma_{M0}} \rightarrow \frac{17,17 \cdot 23,5}{1,05} = 384,28kN$$

$$\frac{N_{Ed}}{N_{c,Rd}} \rightarrow \frac{18,15}{384,28} = 0,05 \leq 1$$

Shear check

$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1,0$$

$$A_v = \frac{2 \cdot A}{\pi} \rightarrow \frac{2 \cdot 17,17}{\pi} = 10,93cm^2$$

$$V_{c\,Rd} = \frac{A_v \cdot \left(\frac{f_y}{\sqrt{3}}\right)}{\gamma_{M0}} \rightarrow \frac{10,93 \cdot \left(\frac{23,5}{\sqrt{3}}\right)}{1,05} = 141,23kN$$

$$\frac{V_{Ed}}{V_{c,Rd}} \rightarrow \frac{2,83}{141,23} = 0,02 \leq 1$$

Bending moment check

$$\frac{M_{Ed}}{M_{c,Rd}} \leq 1,0$$

$$M_{c,Rd} = \frac{W_{pl} f_y}{\gamma_{M0}} \rightarrow \frac{59,77 \cdot 23,5}{1,05} = 1338kNcm \rightarrow 13,38kNm$$

$$\frac{M_{Ed}}{M_{c,Rd}} \rightarrow \frac{7,05}{13,38} = 0,53 \leq 1$$

Combined axial force and bending moment check

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rd}} + \frac{M_{z,Ed}}{M_{z,Rd}} \leq 1 \rightarrow$$

$$\frac{18,15}{384,28} + \frac{1,31}{13,38} + \frac{7,05}{13,38} = 0,671 \leq 1$$

Element ID: 10164 LC3

Flexural buckling check

L: 500cm k:1

$N_{Ed}: 49,89kN$

$$N_{cr} = \frac{\pi^2 \cdot E \cdot I_{y,z}}{L_c^2} \rightarrow \frac{\pi^2 \cdot 21000 \cdot 256,92}{500^2} = 212,999$$

Non– dimensional slenderness

$$\bar{\lambda}_{y,z} = \sqrt{\frac{A \cdot f_y}{N_{cr}}} \rightarrow \sqrt{\frac{17,17 \cdot 23,5}{212,999}} = 1,376$$

Buckling curve c $\rightarrow$ imperfection factor α : 0,49

$$\phi = 0,5 \cdot \left(1 + \alpha\left(\bar{\lambda} - 0,2\right) + \bar{\lambda}^2\right) \rightarrow$$

$$0,5 \cdot \left(1 + 0,49 \cdot (1,376 - 0,2) + 1,376^2\right) = 1,735$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} but\ \chi \le 1 \quad \rightarrow \frac{1}{1,735 + \sqrt{1,735^2 - 1,376^2}} = 0,358$$

Design buckling resistance

$$N_{b,Rd} = \frac{\chi \cdot A \cdot f_y}{\gamma_{M1}} \rightarrow \frac{0,358 \cdot 17,17 \cdot 23,5}{1,05} = 137,573kN$$

$$\frac{N_{Ed}}{N_{b,Rd}} = \frac{49,89}{137,573} = 0,363 \le 1$$

Combined bending moment and compression check

$M2: \ -0,01 \quad - \quad -0,11kNm$

$M3: \ 1,58 \quad - \quad -1,45kNm$

$\bar{\lambda}_{y,z} = 1,376 \qquad \chi_{y,z} = 0,358$

$$M_{Rk} = W_{pl} \cdot f_y \rightarrow 59,77 \cdot 23,5 = 1404,59kNcm \rightarrow 14,05kNm$$

$$N_{Rk} = A \cdot f_y \rightarrow 17,17 \cdot 23,5kN / cm^2 = 403,5kN$$

$\chi_{LT} = 1$

$$C_{my} = 0.636 \rightarrow (0,6 + 0,4 \cdot \psi) \ge 0,4 \quad \psi = \frac{-0,01}{-0,11} = 0,091 \rightarrow$$

$$(0,6 + 0,4 \cdot 0,091) = 0,636$$

$$C_{m<} = 0.4 \rightarrow (0,6 + 0,4 \cdot \psi) \ge 0,4 \quad \psi = \frac{1,58}{-1,45} = -1,09 \rightarrow$$

$$(0,6 + 0,4 \cdot (-1,09)) = 0,164$$

$$K_{yy} = C_{my} \cdot \left(1 + \left(\bar{\lambda}_y - 0.2\right) \cdot \frac{N_{Ed}}{\chi_y \cdot N_{Rk} / \gamma_{M1}}\right) \leq C_{my} \cdot \left(1 + 0,8 \cdot \frac{N_{Ed}}{\chi_y \cdot N_{Rk} / \gamma_{M1}}\right) \rightarrow$$

$$0,636 \cdot \left(1 + (1,376 - 0.2) \cdot \frac{49,89}{0,358 \cdot 403,5 / 1,05}\right) = 0,907 \leq 0,636. \left(1 + 0,8 \cdot \frac{49,89}{0,358 \cdot 403,5 / 1,05}\right) = 0,821 \rightarrow K_{yy} = 0,821$$

$$K_{zz} = C_{mz} \cdot \left(1 + \left(\bar{\lambda}_y - 0.2\right) \cdot \frac{N_{Ed}}{\chi_z \cdot N_{Rk} / \gamma_{M1}}\right) \leq C_{my} \cdot \left(1 + 0,8 \cdot \frac{N_{Ed}}{\chi_z \cdot N_{Rk} / \gamma_{M1}}\right) \rightarrow$$

$$0.4 \cdot \left(1 + (1,376 - 0.2) \cdot \frac{49,89}{0,358 \cdot 403,5 / 1,05}\right) = 0,571 \leq 0,4. \left(1 + 0,8. \frac{49,89}{0,358 \cdot 403,5 / 1,05}\right) = 0,516 \rightarrow K_{zz} = 0,516$$

$$K_{zy,} = 0,6 \cdot K_{yy} \rightarrow 0,6 \cdot 0,821 = 0,493 \qquad K_{yz} = 0,6 \cdot K_{zz} \rightarrow 0,6 \cdot 0,516 = 0,31$$

$$\frac{N_{Ed}}{\chi_y \cdot N_{xx} / \gamma_{M1}} + K_{yy} \cdot \frac{M_{Ed}}{\chi_{LT} \cdot M_{y,Rk} / \gamma_{M1}} + K_{yz} \cdot \frac{M_{z,Ed}}{\chi_{LT} \cdot M_{z,Rk} / \gamma_{M1}} \leq 1 \rightarrow \frac{49,89}{0,358 \cdot 403,5 / 1,05} + 0,821 \cdot \frac{0,11}{1 \cdot 14,05 / 1,05} + 0,31 \cdot \frac{1,58}{1 \cdot 14,05 / 1,05} = 0,406 \leq 1$$

$$\frac{N_{Ed}}{\chi_z \cdot N_{xx} / \gamma_{M1}} + K_{zy} \cdot \frac{M_{Ed}}{\chi_{LT} \cdot M_{y,Rk} / \gamma_{M1}} + K_{zz} \cdot \frac{M_{z,Ed}}{\chi_{LT} \cdot M_{z,Rk} / \gamma_{M1}} \leq 1 \rightarrow \frac{49,89}{0,358 \cdot 403,5 / 1,05} + 0,493 \cdot \frac{0,11}{1 \cdot 14,05 / 1,05} + 0,516 \cdot \frac{1,58}{1 \cdot 14,05 / 1,05} = 0,428 \leq 1$$

7.3 Suspension truss (p3) check

CHS 48,3x5

Element ID: 10156 LC6

$N_{Ed}:64,78kN$

$A:6,8cm^2 \quad I_{yy,zz}:16,15cm^4 \quad W_{pl,y,z}:9,42cm^3$

$f_y:235N/mm^2 \quad f_u:360N/mm^2 \quad t \leq 40mm$

$E:210000N/mm^2$

Cross section classification

$$\varepsilon = \sqrt{\frac{235}{f_y}} \rightarrow \sqrt{\frac{235}{235}} = 1$$

$$\frac{d}{t} \cdot \varepsilon^2 \leq 50 \cdot \varepsilon^2 \rightarrow \frac{4,83}{0,5} \cdot 1^2 \leq 50 \cdot 1 \quad \text{section class 1}$$

Tension check

$$\frac{N_{Ed}}{N_{c,Rd}} \leq 1,0$$

$$N_{Rd} = \frac{A \cdot f_y}{\gamma_{M0}} \rightarrow \frac{6,8 \cdot 23,5}{1,05} = 152,19kN$$

$$\frac{N_{Ed}}{N_{Rd}} \rightarrow \frac{64,78}{152,19} = 0,426 \leq 1$$

Element ID: 10156 LC3

Flexural buckling check

L:325cm k:1

$N_{Ed}:-19,51kN$

$$N_{cr} = \frac{\pi^2 \cdot E \cdot I_{y,z}}{L_c^2} \rightarrow \frac{\pi^2 \cdot 21000 \cdot 16,15}{325^2} = 31,69$$

Non-dimensional slenderness

$$\bar{\lambda}_{y,z} = \sqrt{\frac{A \cdot f_y}{N_{cr}}} \rightarrow \sqrt{\frac{6,8 \cdot 23,5}{31,69}} = 2,246$$

Buckling curve c $\rightarrow$ imperfiction factor α : 0,49

$$\phi = 0,5 \cdot \left(1 + \alpha\left(\bar{\lambda} - 0,2\right) + \bar{\lambda}^2\right) \rightarrow$$

$$0,5 \cdot \left(1 + 0,49 \cdot (2,246 - 0,2) + 2,246^2\right) = 3,524$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \; but \; \chi \leq 1 \quad \rightarrow \frac{1}{3,524 + \sqrt{3,524^2 - 2,246^2}} = 0,16$$

Design buckling resistance

$$N_{b,Rd} = \frac{\chi \cdot A \cdot f_y}{\gamma_{M1}} \rightarrow \frac{0,16 \cdot 6,8 \cdot 23,5}{1,05} = 24,35kN$$

$$\frac{N_{Ed}}{N_{b,Rd}} = \frac{19,51}{24,35} = 0,801 \leq 1$$

7.4 Arch beam (p4) check

CHS139,7x6

Element ID:10075 LC6

$N_{Ed}: -29,8kN \quad M_{y,Ed}: 3,30kNm \quad M_{z,Ed}: -8,94kNm$

$V_{y,Ed}: -14,16kN \quad V_{z,Ed}: 1,82kN$

$A: 25,20cm^2 \quad I_{yy,zz}: 564,26cm^4 \quad W_{pl,y,z}: 107,33cm^3$

$f_y: 235N/mm^2 \quad f_u: 360N/mm^2 \quad t \leq 40mm$

$E: 210000N/mm^2$

Cross section classification

$$\varepsilon = \sqrt{\frac{235}{f_y}} \rightarrow \sqrt{\frac{235}{235}} = 1$$

$$\frac{d}{t} \cdot \varepsilon^2 \leq 50 \cdot \varepsilon^2 \rightarrow \frac{13,97}{0,6} \cdot 1^2 \leq 50 \cdot 1 \quad \text{section class 1}$$

Compression check

$$\frac{N_{Ed}}{N_{c,Rd}} \leq 1,0$$

$$N_{c,Rd} = \frac{A \cdot f_y}{\gamma_{M0}} \rightarrow \frac{25,20 \cdot 23,5}{1,05} = 564kN$$

$$\frac{N_{Ed}}{N_{c,Rd}} \rightarrow \frac{29,8}{564} = 0,05 \leq 1$$

Shear check

$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1,0$$

$$A_v = \frac{2 \cdot A}{\pi} \rightarrow \frac{2 \cdot 25,20}{\pi} = 16,04cm^2$$

$$V_{cRd} = \frac{A_v \cdot \left(\frac{f_y}{\sqrt{3}}\right)}{\gamma_{M0}} \rightarrow \frac{16,04 \cdot \left(\frac{23,5}{\sqrt{3}}\right)}{1,05} = 207,26kN$$

$$\frac{V_{Ed}}{V_{c,Rd}} \rightarrow \frac{14,16}{207,26} = 0,07 \leq 1$$

Bending moment check

$$\frac{M_{Ed}}{M_{c,Rd}} \leq 1,0$$

$$M_{c,Rd} = \frac{W_{pl} \cdot f_y}{\gamma_{M0}} \rightarrow \frac{107,33 \cdot 23,5}{1,05} = 2402kNcm \rightarrow 24,02kNm$$

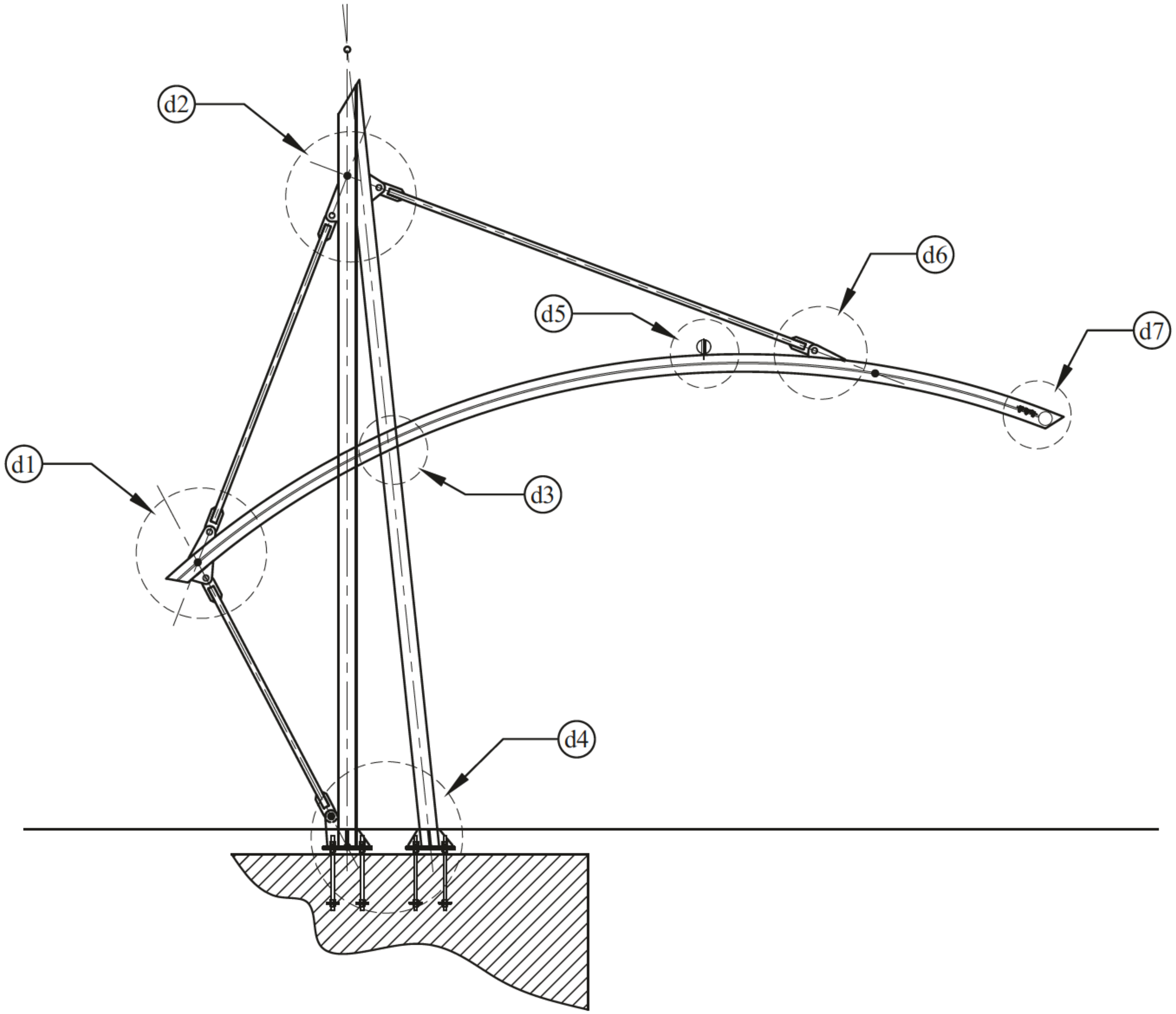
$$\frac{M_{Ed}}{M_{c,Rd}} \rightarrow \frac{8,94}{24,02} = 0,37 \leq 1$$

Combined axial force and bending moment check

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rd}} + \frac{M_{z,Ed}}{M_{z,Rd}} \leq 1 \rightarrow$$

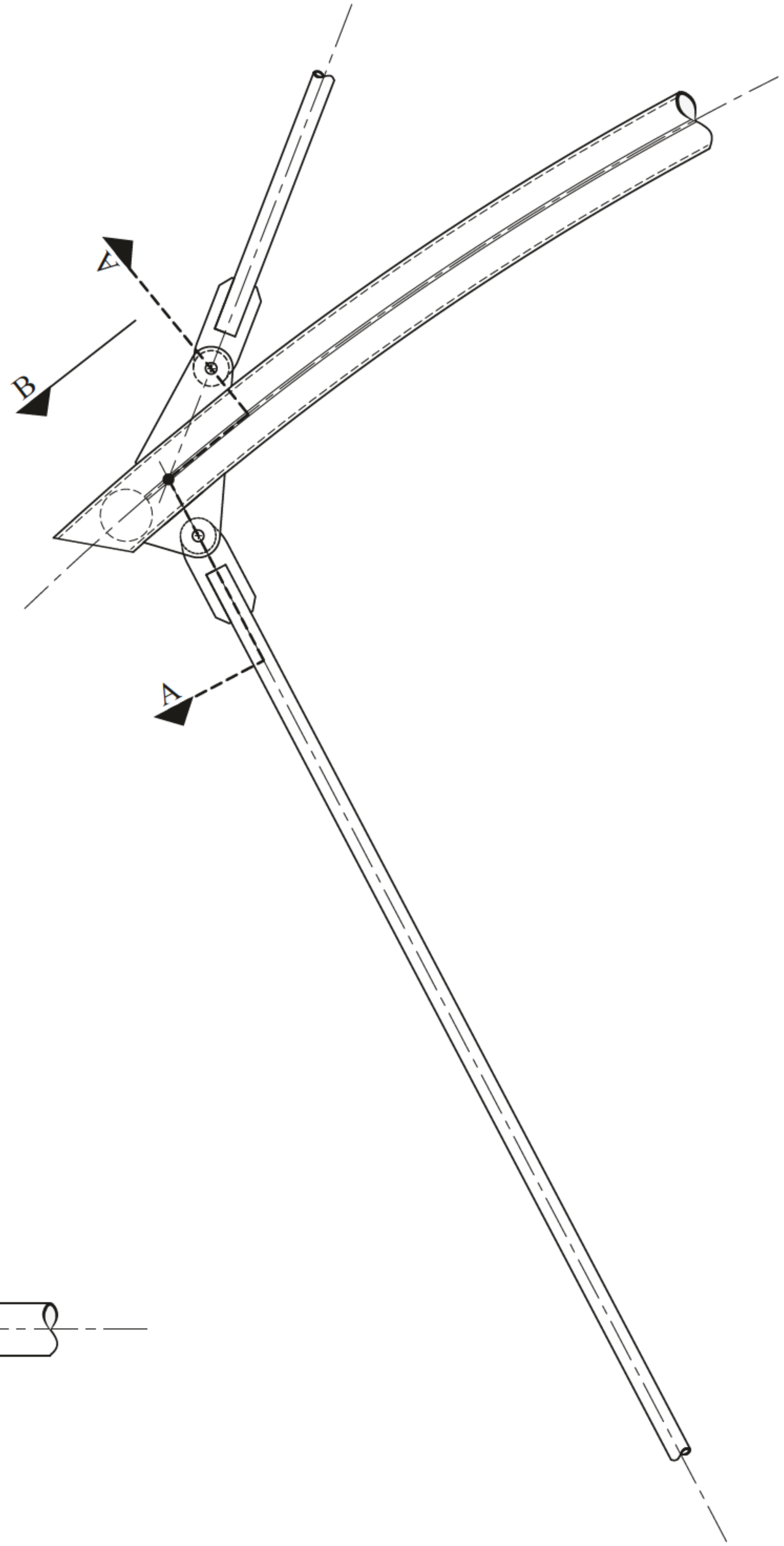
$$\frac{29,8}{564} + \frac{3,3}{24,02} + \frac{8,94}{24,02} = 0,562 \leq 1$$

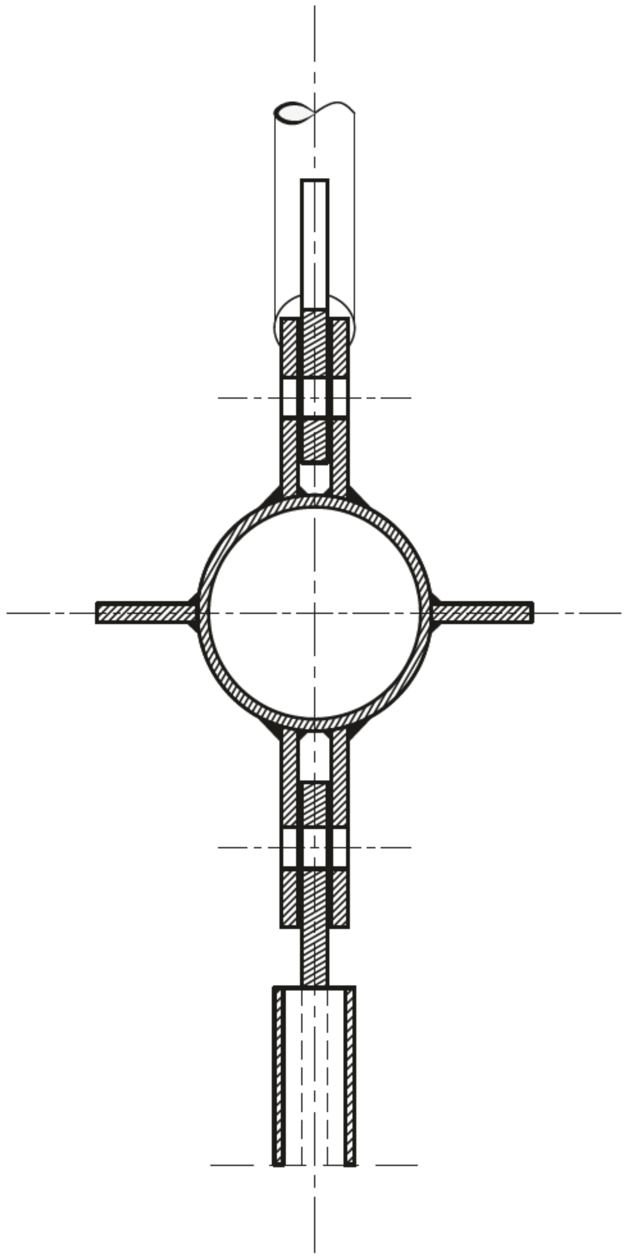
8. Construction details



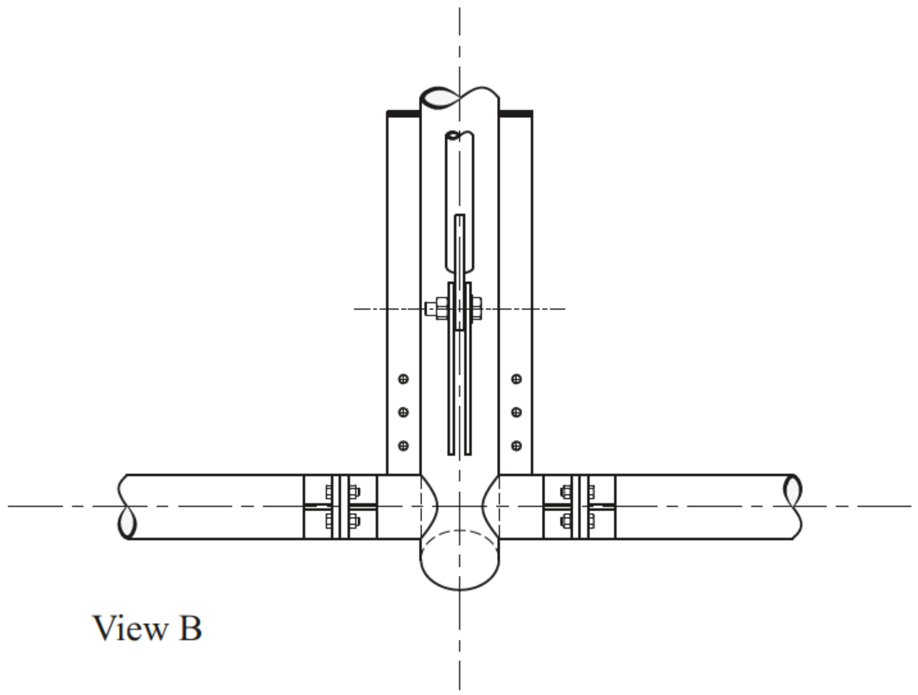
All dimensions are in unit mm.

8.1 Detail d1



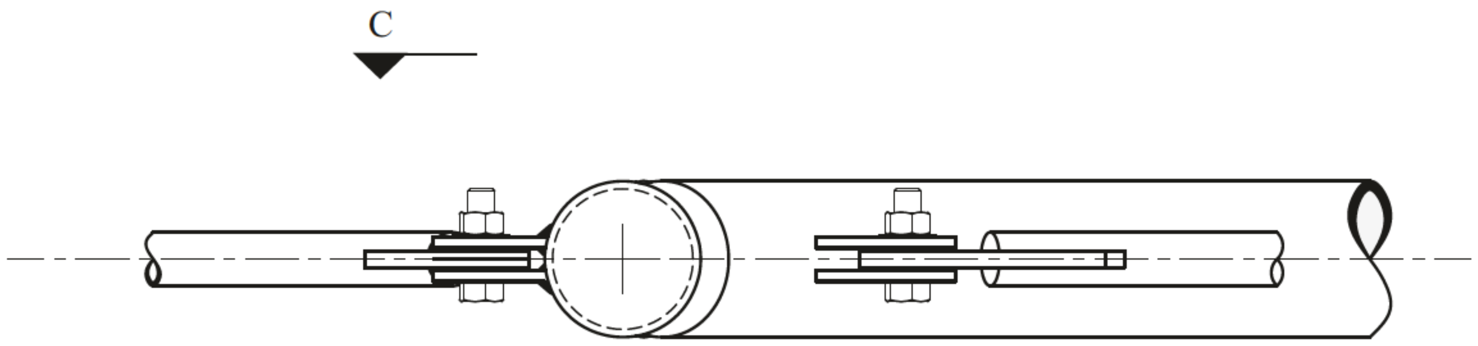


Section A-A

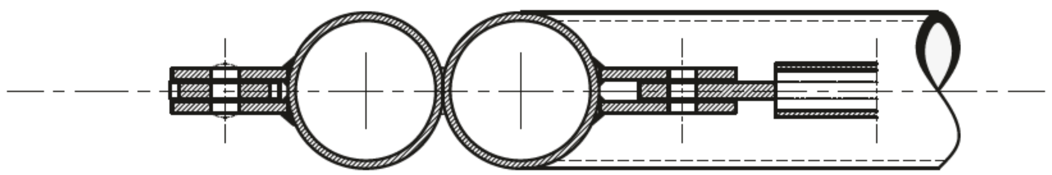


View B

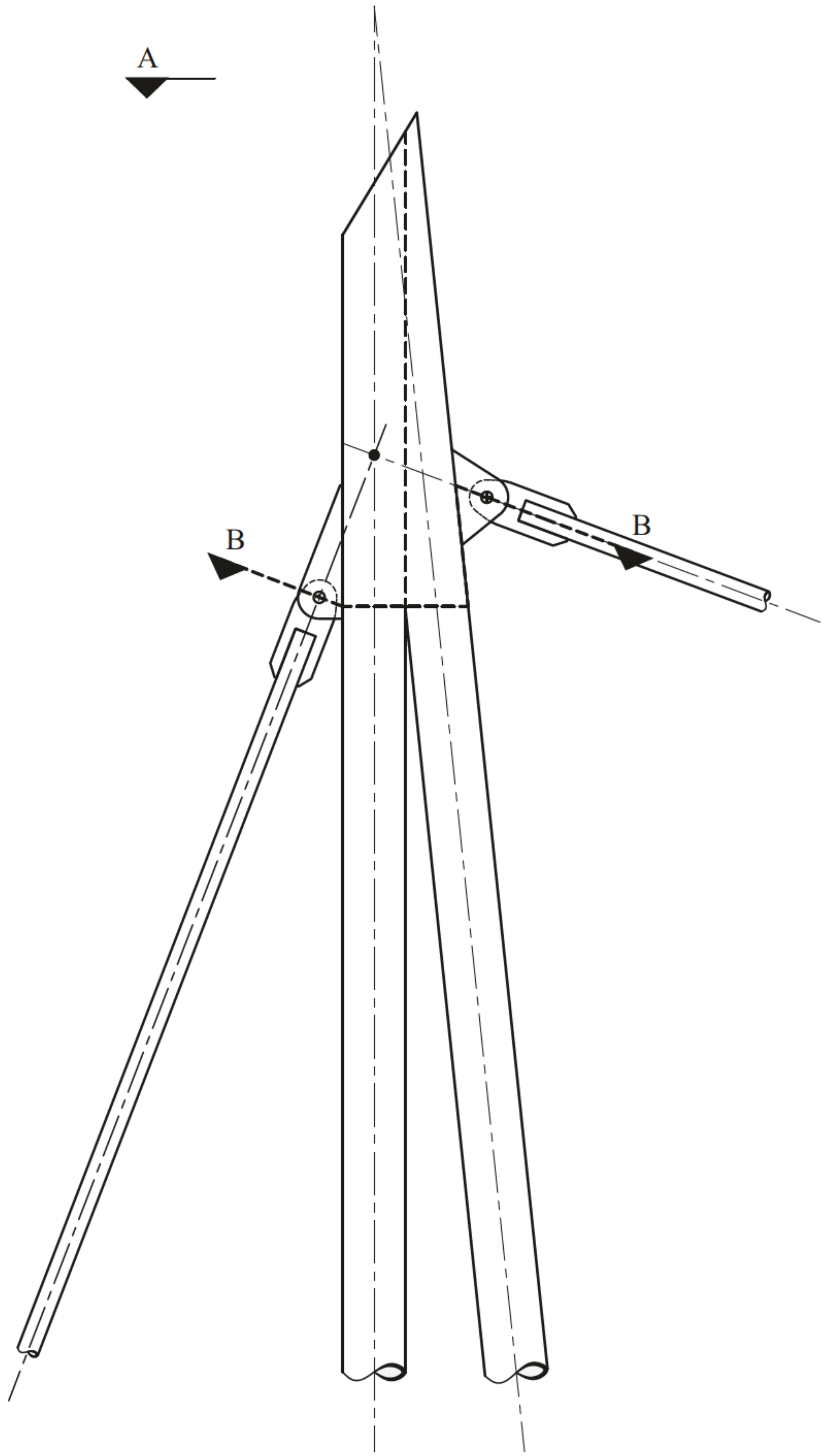
8.2 Detail d2



View A

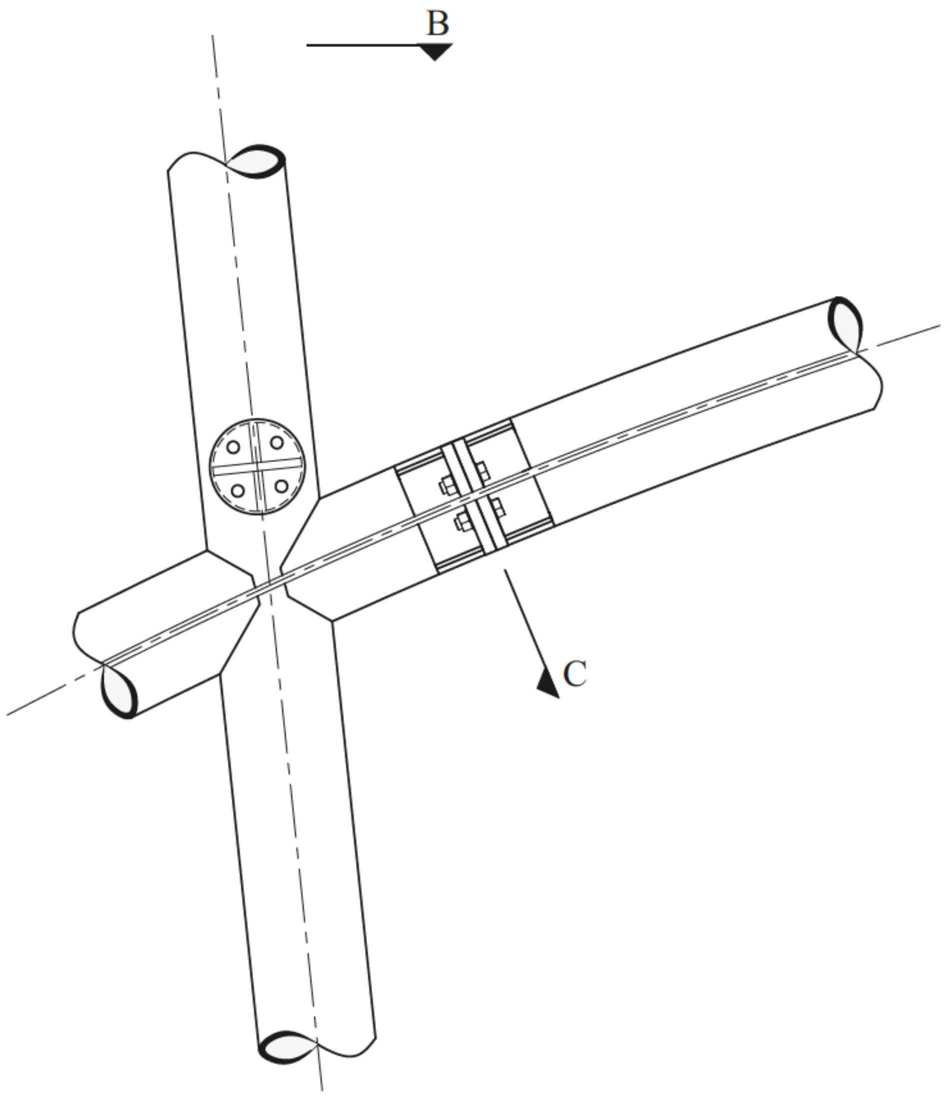


Section B-B

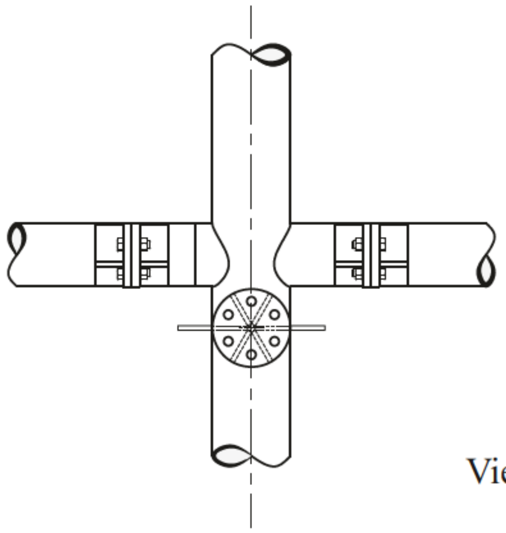


View C

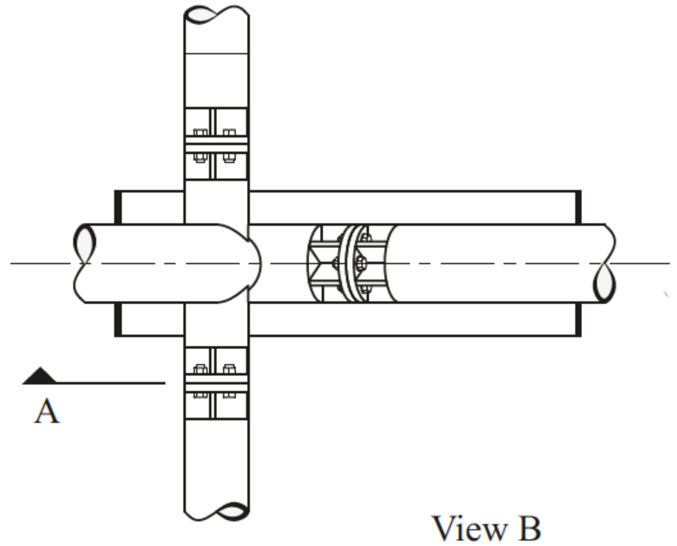
8.3 Detail d3



View A

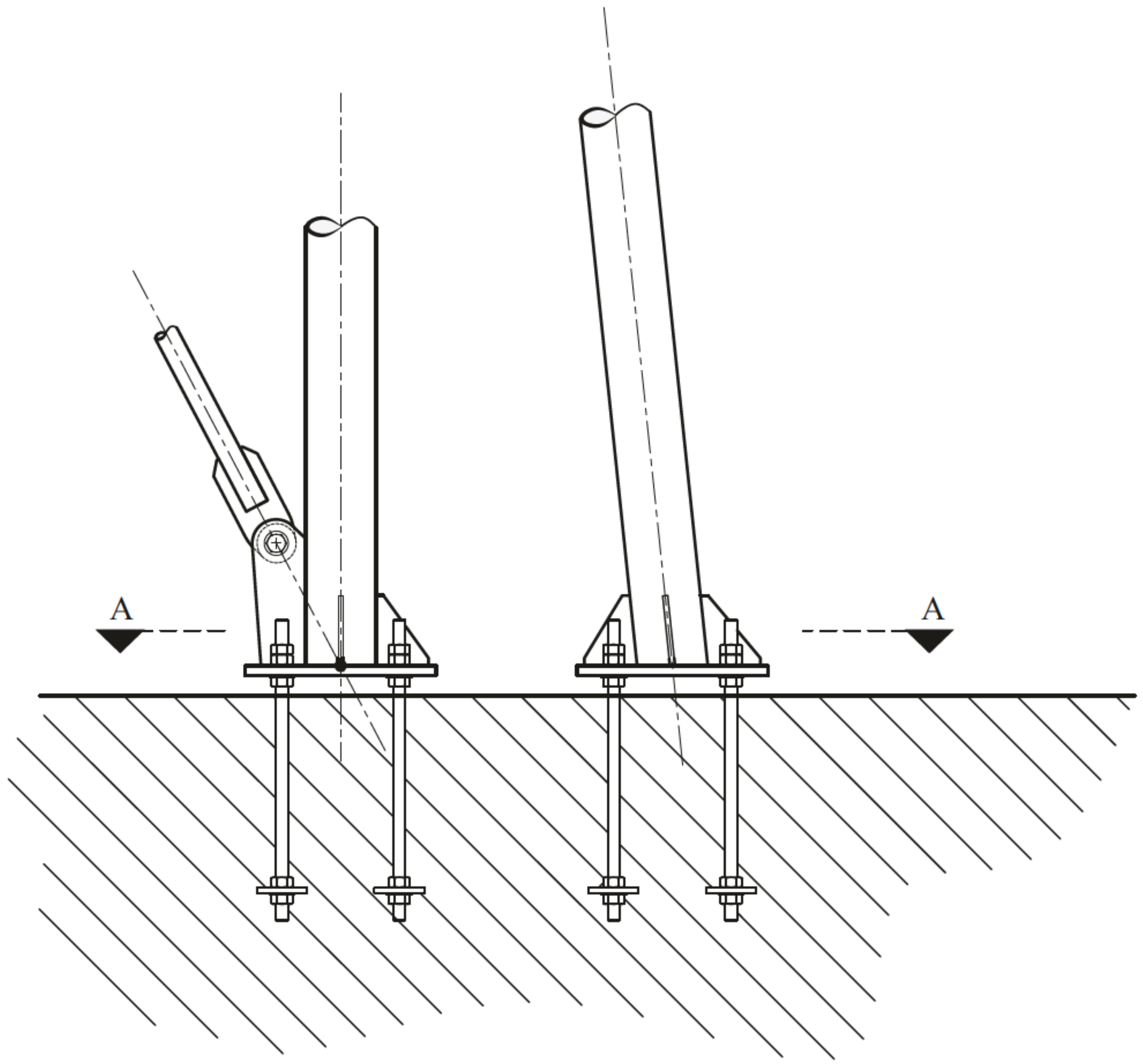


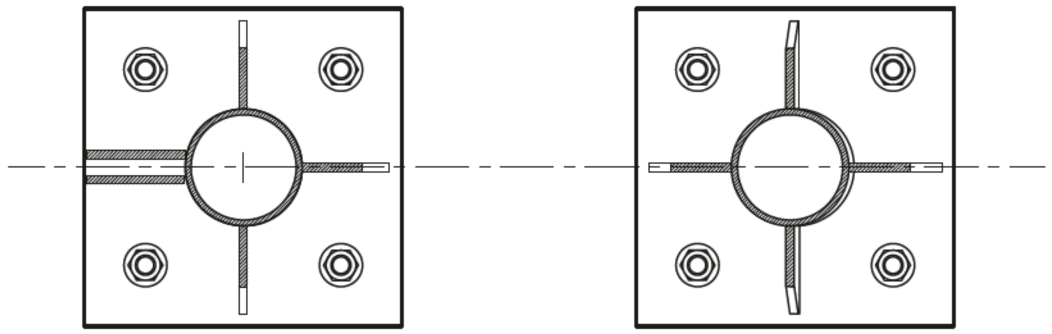
View C



View B

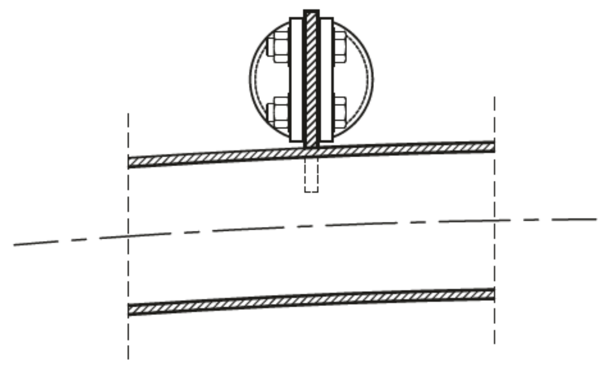
8.4 Detail d4



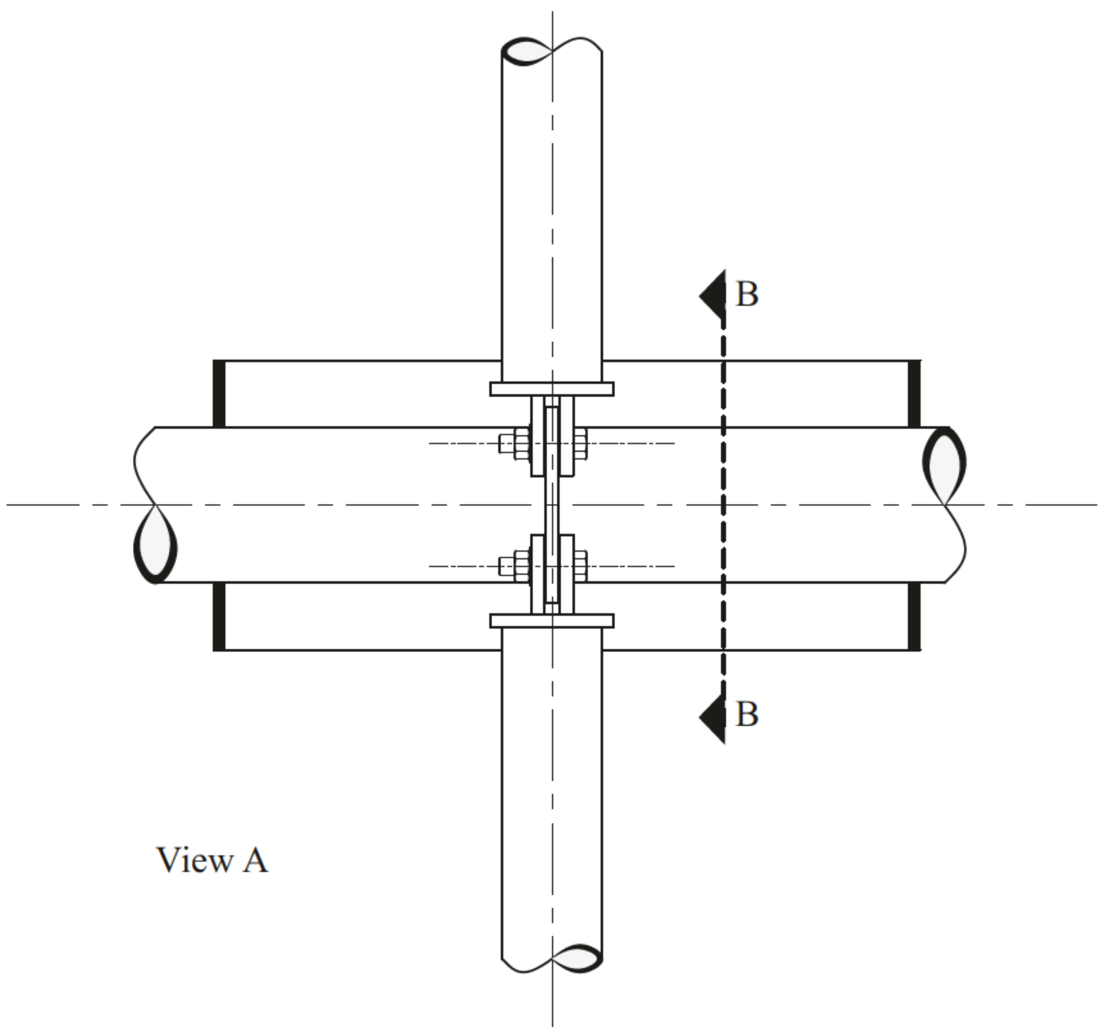


Section A-A

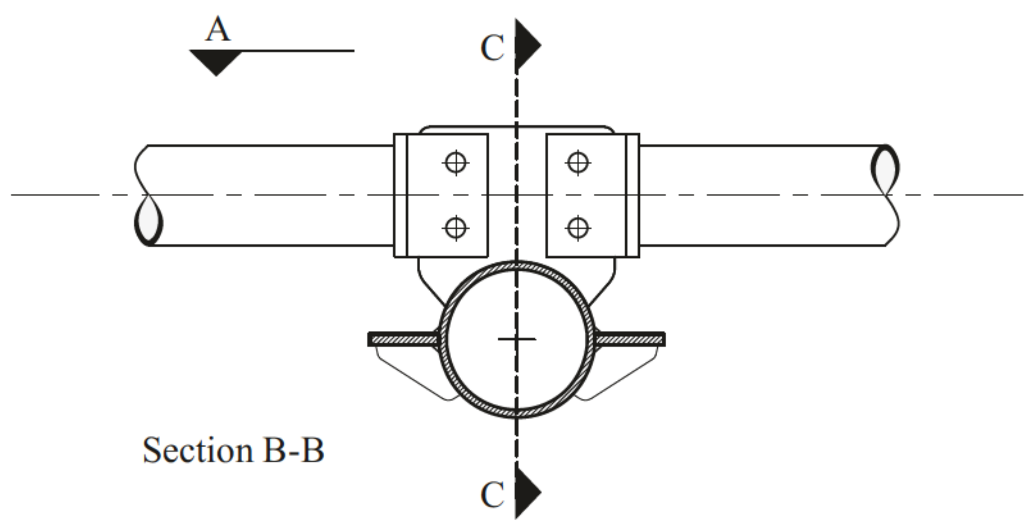
8.5 Detail d5



Section C-C

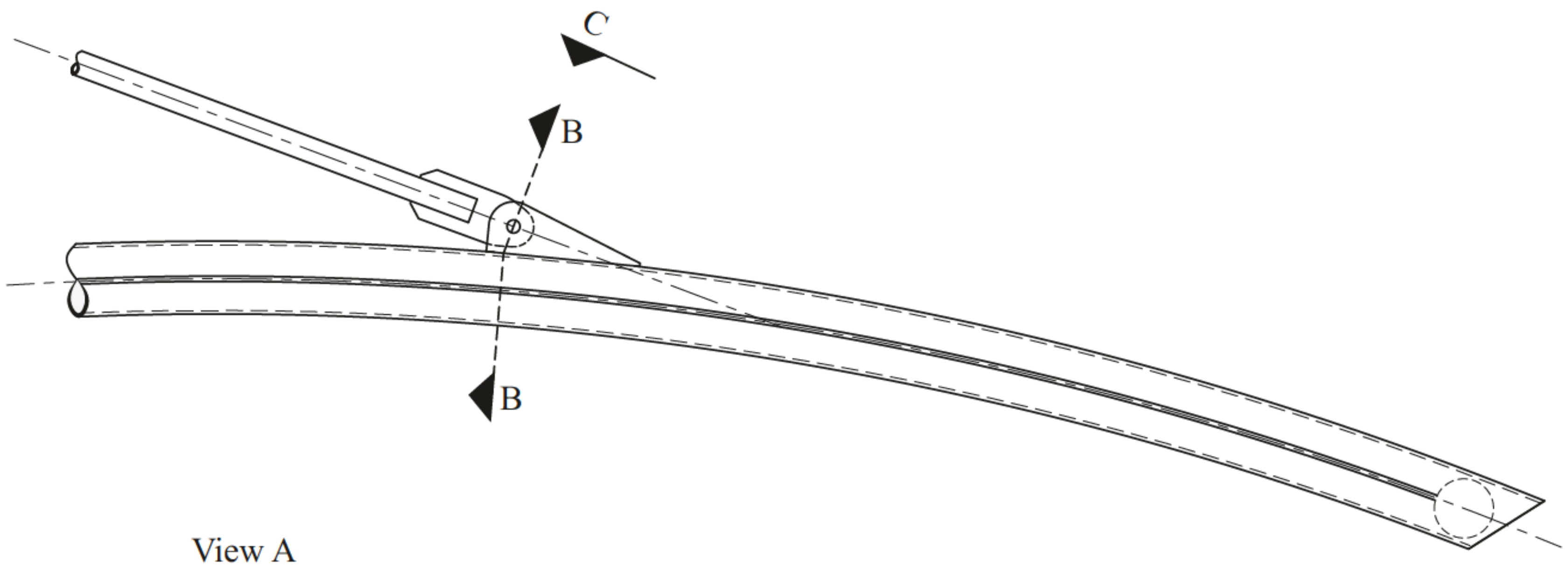


View A

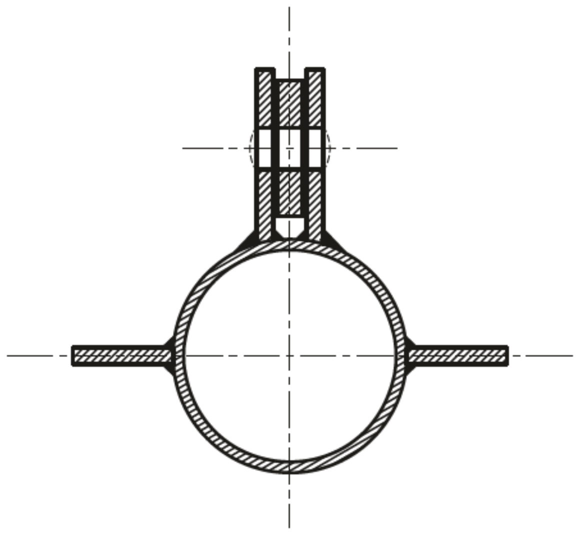


Section B-B

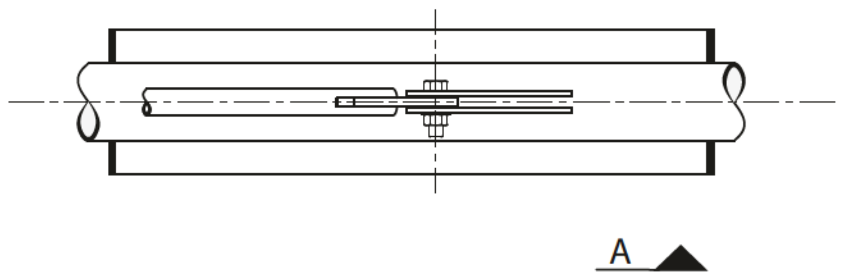
8.6 Detail d6



View A

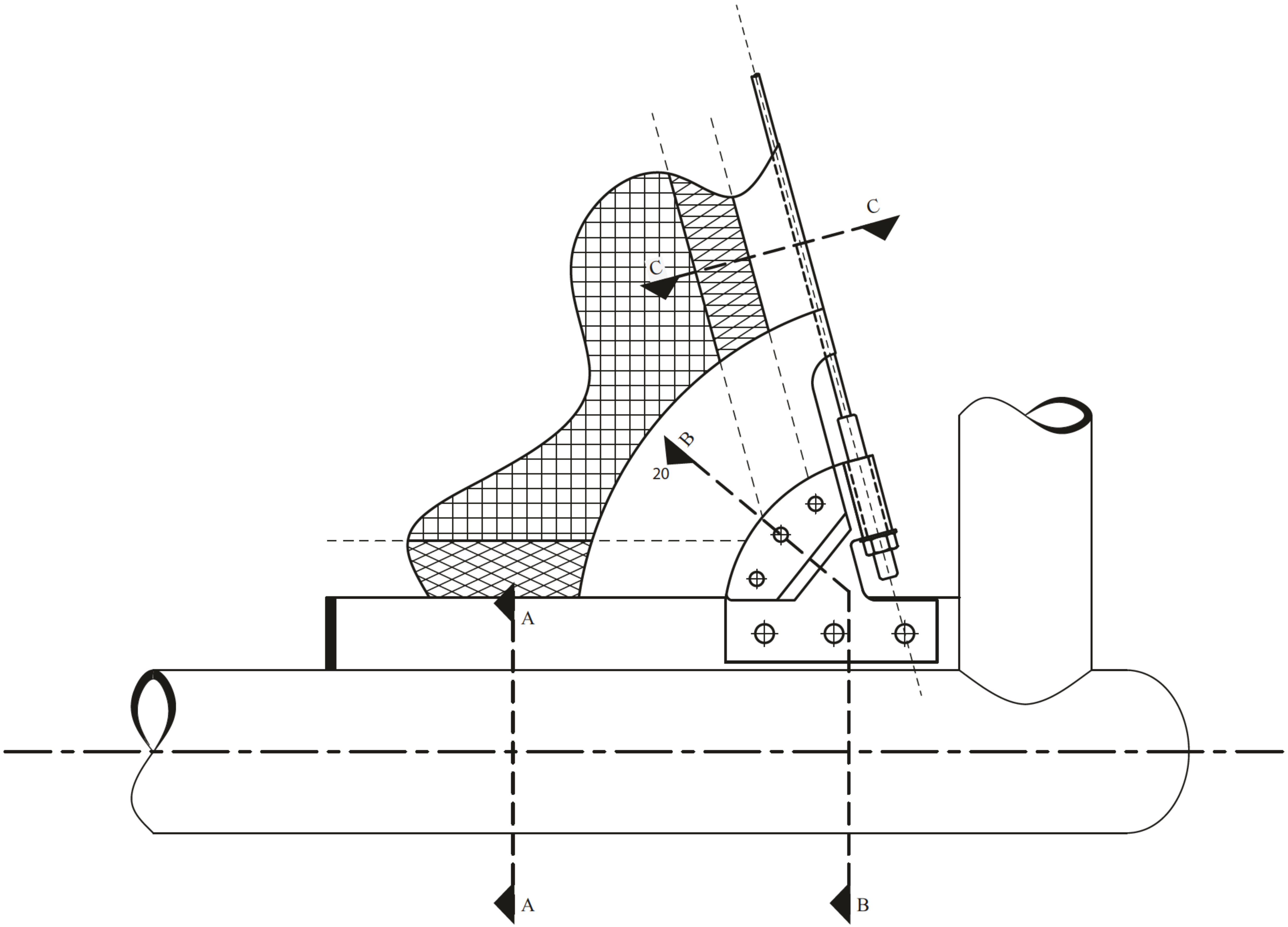


Section B-B

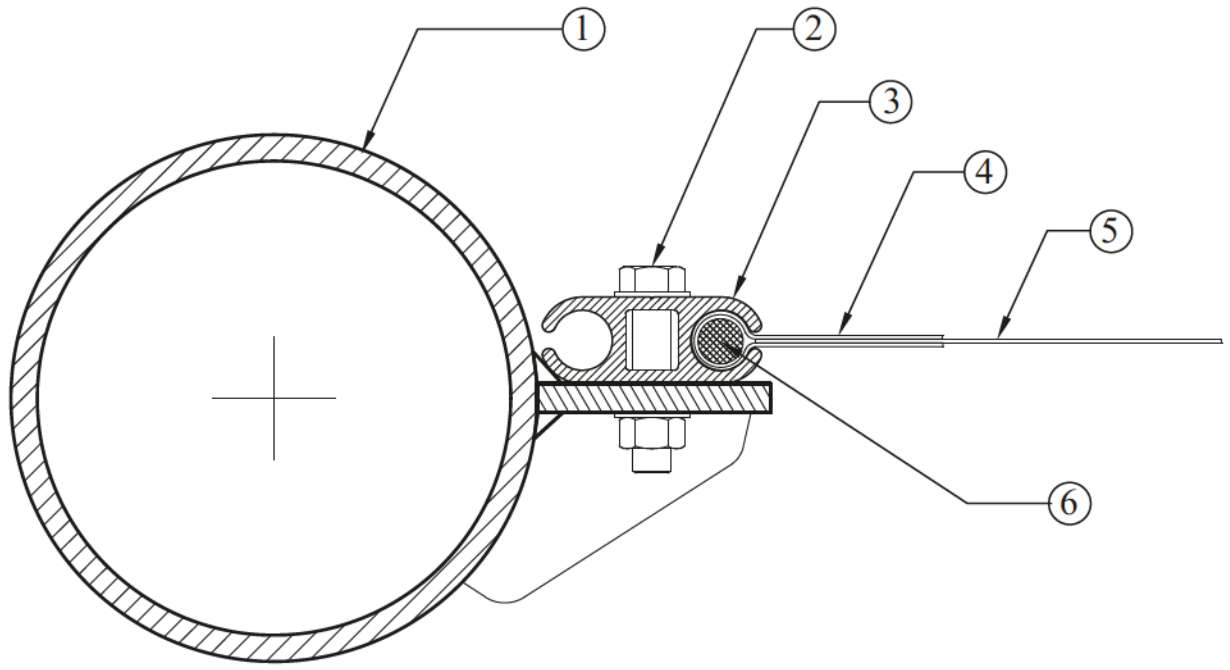


View C

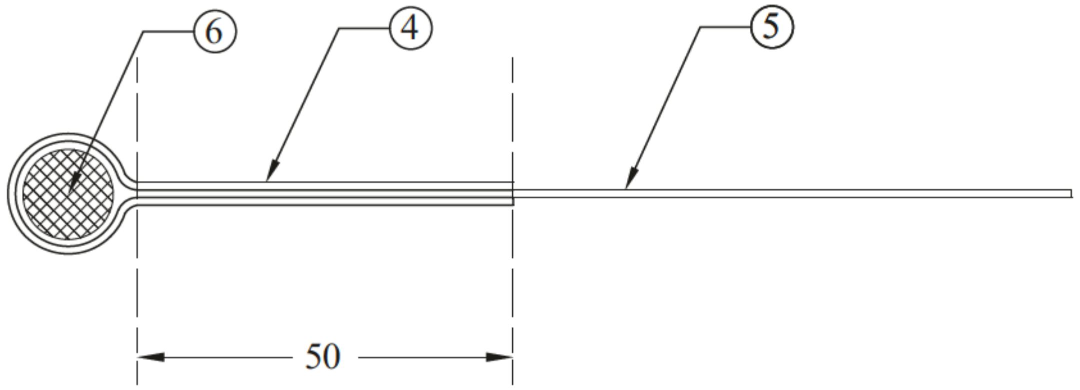
8.7.1 Detail d7



8.7.2 Detail d7 - A section

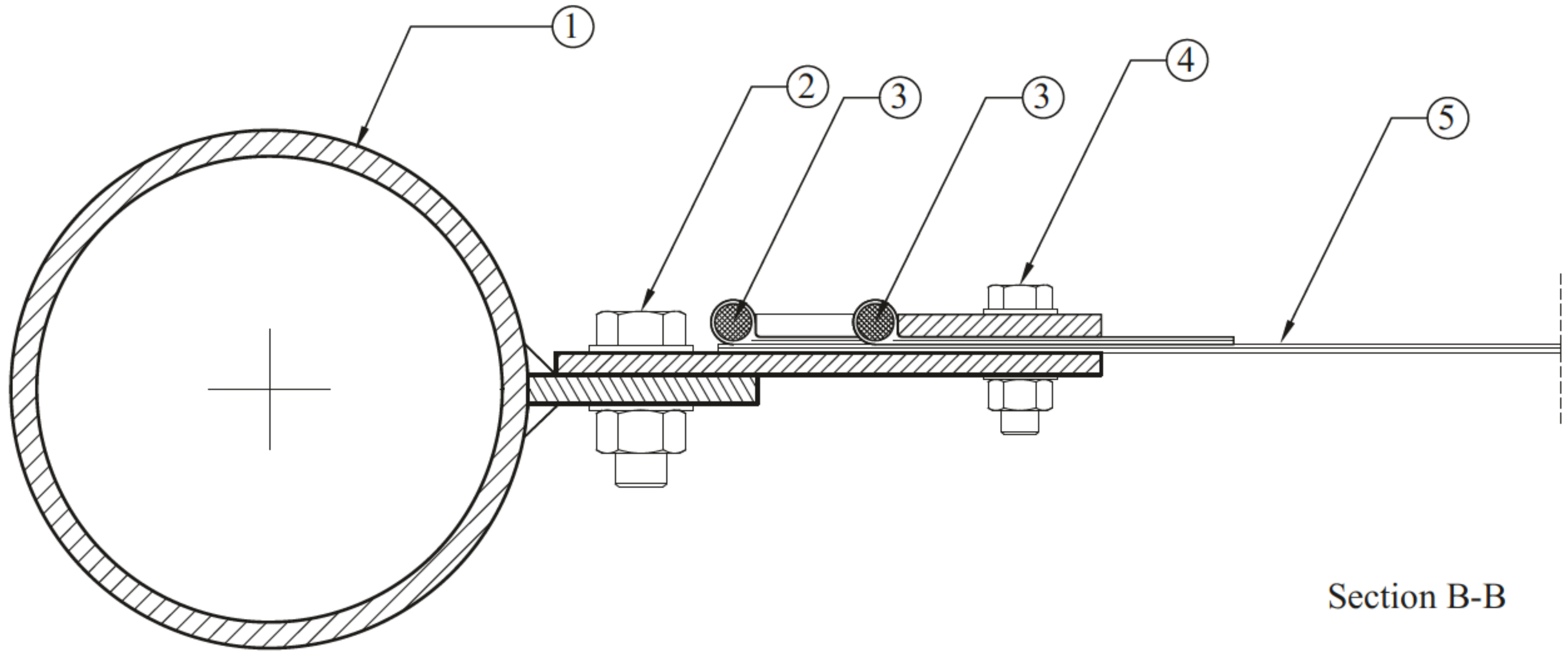


Section A-A



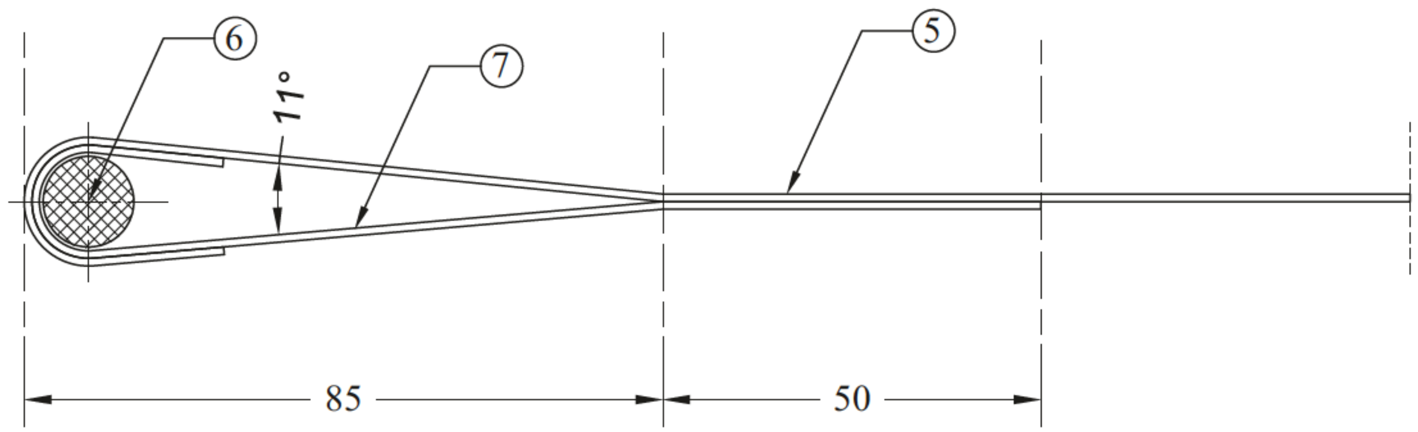
1. CHS 139.7x6mm
2. Bolt (Aluminum - Construction)
3. Aluminum extrusion profile
4. Membrane
5. Base membrane fabric
6. EPDM solid

8.7.3 Detail d7 - B and C sections



Section B-B

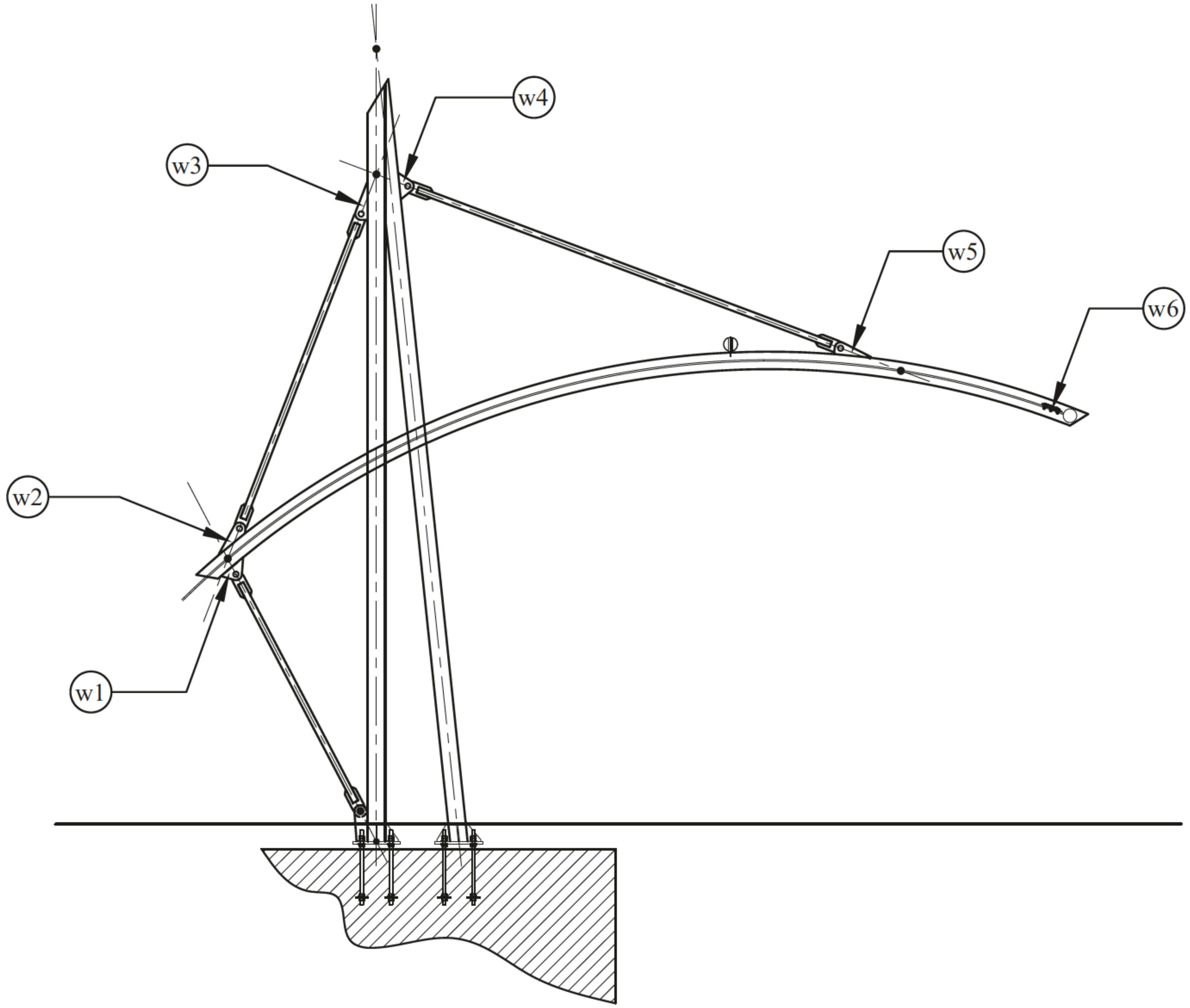
1. CHS 139.7x6mm
2. Bolt (Corner plate - construction)
3. EPDM solid
4. Bolt (Corner plate - membrane)
5. Base membrane fabric
6. Border steel cable
7. Additional part of the border cable pocked



Section C-C

9. Construction details check

Some important welding details were checked according to the EN 1993-1-8.
Shear and tension adequacy of connection plates were checked according to the EN 1993-1-1.



All dimensions are in unit mm.

9.1 Weld check w1

Weld resistance check

$$F = 31{,}92kN \qquad a = 3mm \qquad l = 234mm$$

$$\beta_w = 0.8 \text{ for} \rightarrow \text{S235} \qquad \gamma_{M2} = 1{,}25$$

$$F_u = 360N/mm^2$$

$$\sqrt{\left(\sigma^2 + t^2\right)} \leq \frac{f_u}{\beta_u \cdot \gamma_{M2} \cdot \sqrt{3}}$$

$$\sigma = \frac{F_v}{A_w} = \frac{F \cdot \cos 13}{4 \cdot 3 \cdot 234} = 11{,}08N/mm^2$$

$$t = \frac{F_h}{A_W} = \frac{\cos 77 \cdot F}{4 \cdot 3 \cdot 234} = 2{,}56N/mm^2$$

$$\sqrt{\left(11{,}08^2 + 2{,}56^2\right)} \leq \frac{360}{0{,}8 \cdot 1{,}25 \cdot \sqrt{3}} \rightarrow 11{,}37 \leq 207{,}85N/mm^2$$

Tension resistance check

$$\frac{N_{Ed}}{N_{t,Rd}} \leq 1{,}0$$

$$N_{Ed} = 31{,}92kN$$

$$N_{t,Rd} = \frac{A_f \cdot f_y}{\gamma_{M0}} = \frac{2 \cdot 2 \cdot 44 \cdot 10 \cdot 235}{1{,}0} = 413{,}6kN$$

$$\frac{N_{Ed}}{N_{t,Rd}} = \frac{31{,}92}{413{,}6} = 0{,}08$$

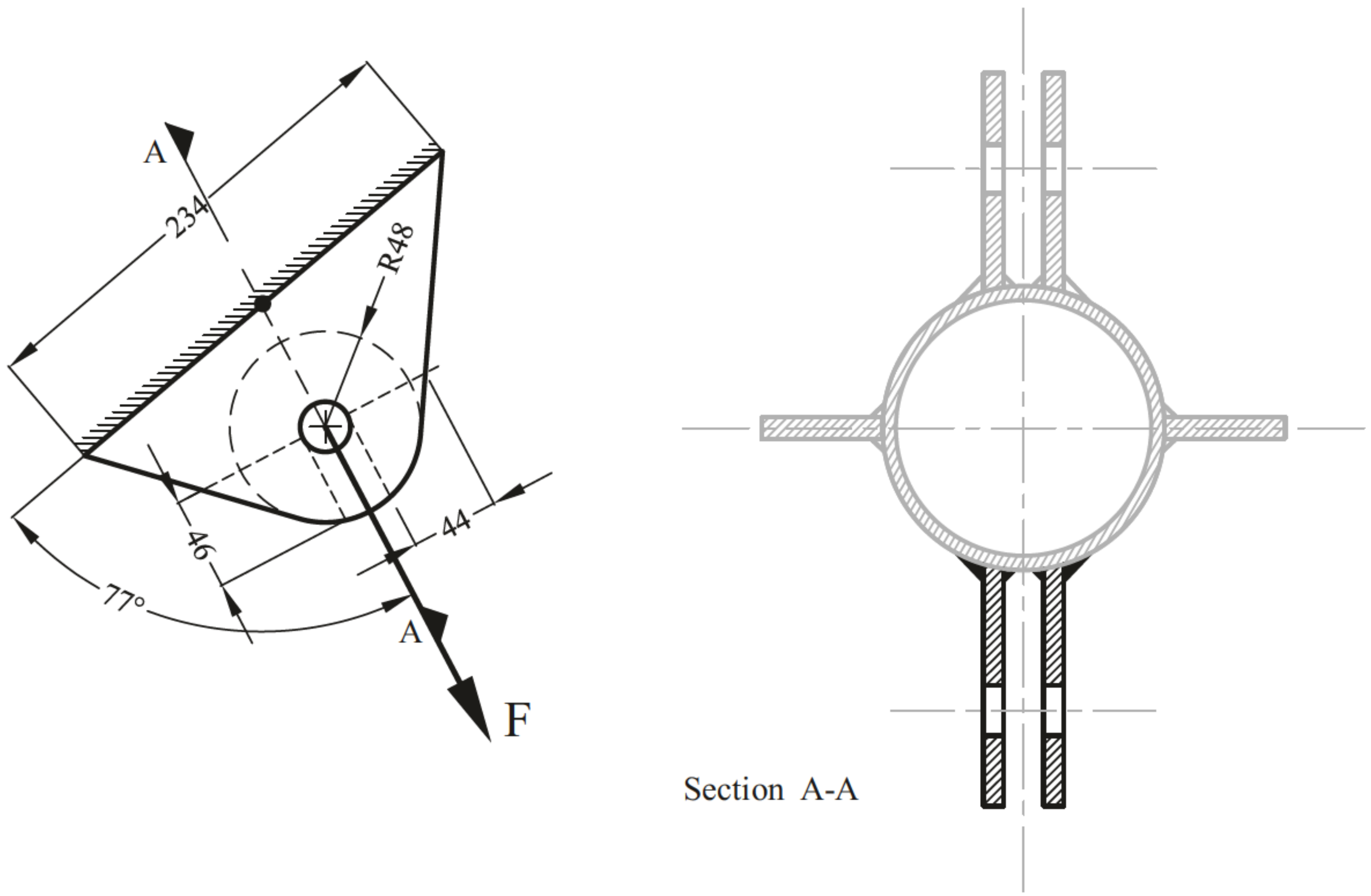
Shear resistance check

$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1.0$$

$$V_{Ed} = 31{,}92kN$$

$$V_{c,Rd} = \frac{A_f \cdot \left(f_y/\sqrt{3}\right)}{\gamma_{M0}} = \frac{2 \cdot 2 \cdot 46 \cdot 10 \cdot \left(235/\sqrt{3}\right)}{1{,}0} = 249{,}6kN$$

$$\frac{V_{Ed}}{V_{c,Rd}} = \frac{31{,}92}{249{,}6} = 0{,}13$$



9.2 Weld check w2

Weld resistance check

$F = 64,47kN \qquad a = 3mm \qquad l = 268mm$

$\beta_w = 0.8 \text{ for} \rightarrow \text{S235} \qquad \gamma_{M2} = 1,25$

$F_u = 360N / mm^2$

$$\sqrt{\left(\sigma^2 + t^2\right)} \leq \frac{f_u}{\beta_u \cdot \gamma_{M2} \cdot \sqrt{3}}$$

$$\sigma = \frac{M}{W_{el,w}} + \frac{F_v}{A_w} = \frac{F \cdot 10}{4 \cdot 3 \cdot \frac{268^2}{6}} + \frac{F \cdot \cos 61}{4 \cdot 3 \cdot 268} = 33,64N / mm^2$$

$$t = \frac{F_h}{A_W} = \frac{F \cdot \cos 29}{4 \cdot 3 \cdot 268} = 17,53N / mm^2$$

$$\sqrt{\left(33,64^2 + 17,53^2\right)} \leq \frac{360}{0,8 \cdot 1,25 \cdot \sqrt{3}} \rightarrow 37,93 \leq 207,85N / mm^2$$

Tension resistance check

$$\frac{N_{Ed}}{N_{t,Rd}} \leq 1,0$$

$N_{Ed} = 64,47kN$

$$N_{t,Rd} = \frac{A_f \cdot f_y}{\gamma_{M0}} = \frac{2 \cdot 2 \cdot 35 \cdot 10 \cdot 235}{1,0} = 329kN$$

$$\frac{N_{Ed}}{N_{t,Rd}} = \frac{64,47}{329} = 0,195$$

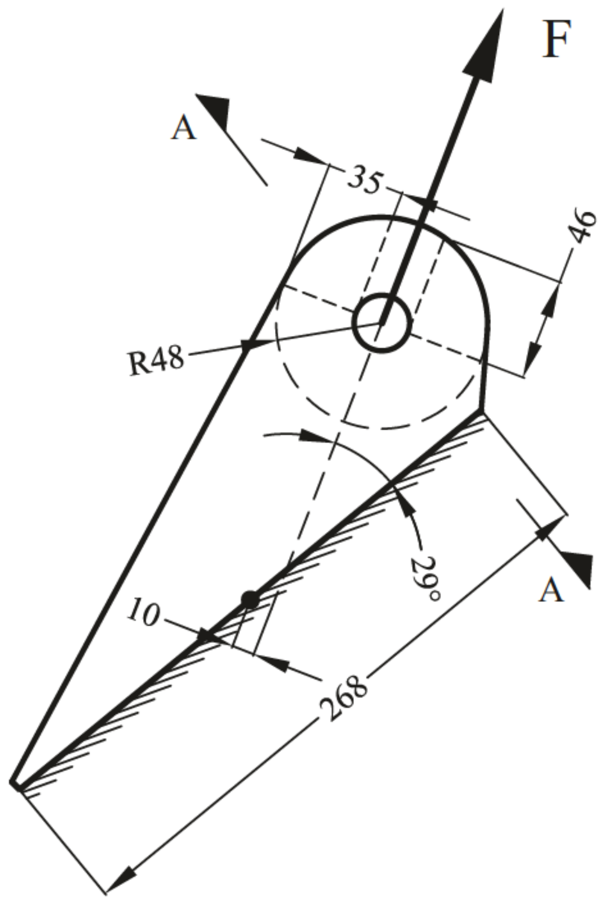
Shear resistance check

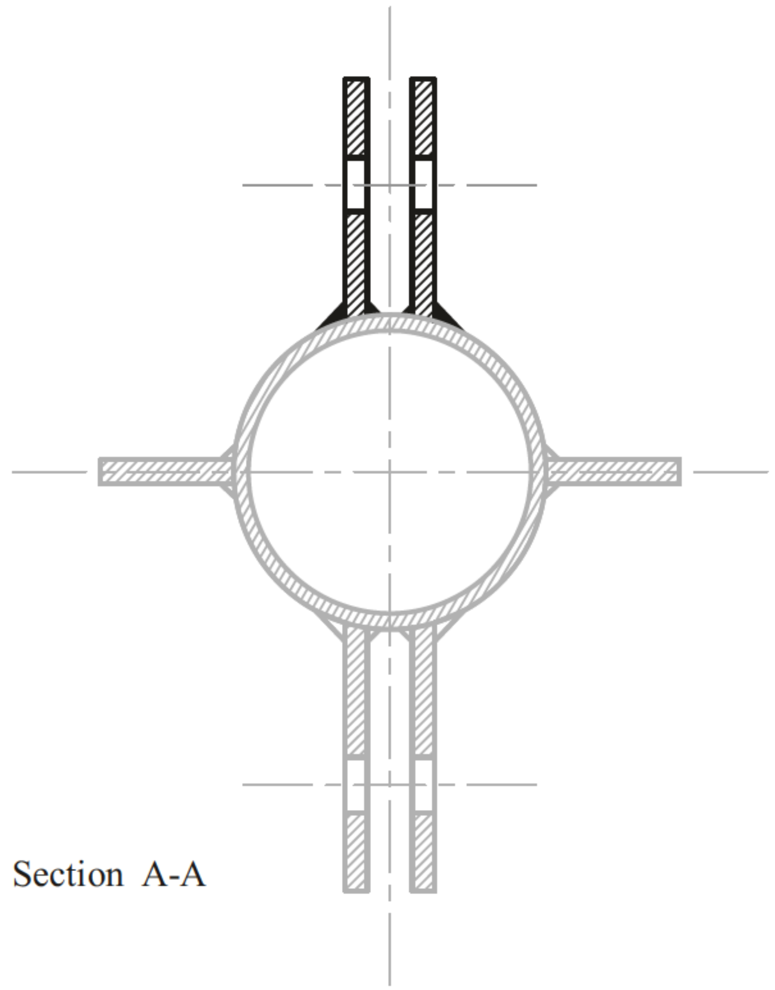
$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1.0$$

$V_{Ed} = 64,47kN$

$$V_{c,Rd} = \frac{A_f \cdot \left(f_y / \sqrt{3}\right)}{\gamma_{M0}} = \frac{2 \cdot 2 \cdot 46 \cdot 10 \cdot \left(235 / \sqrt{3}\right)}{1,0} = 249,6kN$$

$$\frac{V_{Ed}}{V_{c,Rd}} = \frac{64,47}{249,6} = 0,258$$





Section A-A

9.3 Weld check w3

Weld resistance check

$F = 64,47kN \quad a = 3mm \quad l = 297mm$

$\beta_w = 0.8 \text{ for} \rightarrow \text{S235} \quad \gamma_{M2} = 1,25$

$F_u = 360N/mm^2$

$$\sqrt{(\sigma^2 + t^2)} \leq \frac{f_u}{\beta_u \cdot \gamma_{M2} \cdot \sqrt{3}}$$

$$\sigma = \frac{M}{W_{el,w}} + \frac{F_v}{A_w} = \frac{F \cdot 13}{4 \cdot 3 \cdot \frac{297^2}{6}} + \frac{F \cdot \cos 21}{4 \cdot 3 \cdot 297} = 21,64N/mm^2$$

$$t = \frac{F_h}{A_W} = \frac{F \cdot \cos 69}{4 \cdot 3 \cdot 297} = 6,48N/mm^2$$

$$\sqrt{(21,64^2 + 6,48^2)} \leq \frac{360}{0,8 \cdot 1,25 \cdot \sqrt{3}} \rightarrow 22,59 \leq 207,85N/mm^2$$

Tension resistance check

$$\frac{N_{Ed}}{N_{t,Rd}} \leq 1,0$$

$N_{Ed} = 64,47kN$

$$N_{t,Rd} = \frac{A_f \cdot f_y}{\gamma_{M0}} = \frac{2 \cdot 2 \cdot 35 \cdot 10 \cdot 235}{1,0} = 329kN$$

$$\frac{N_{Ed}}{N_{t,Rd}} = \frac{64,47}{329} = 0,195$$

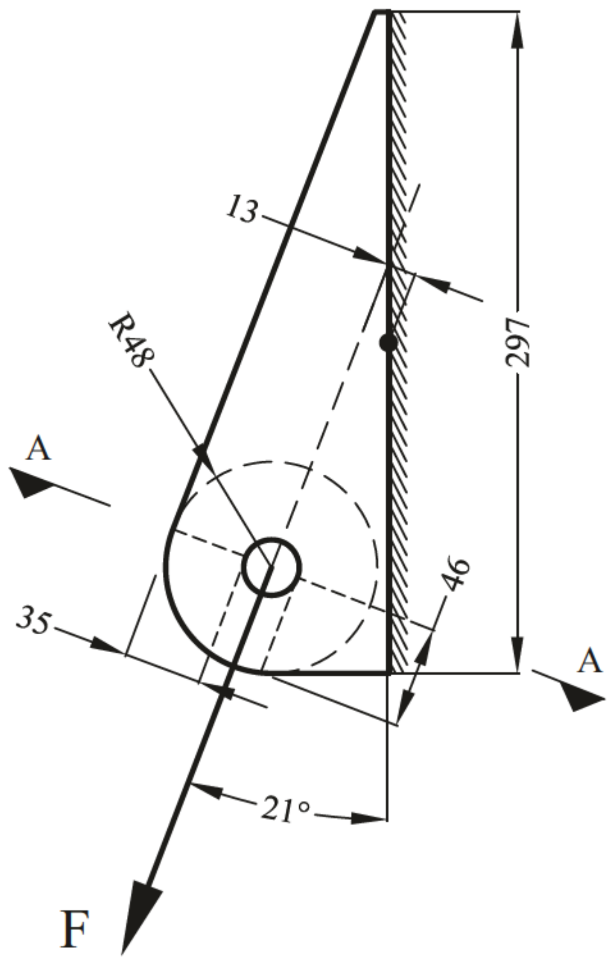
Shear resistance check

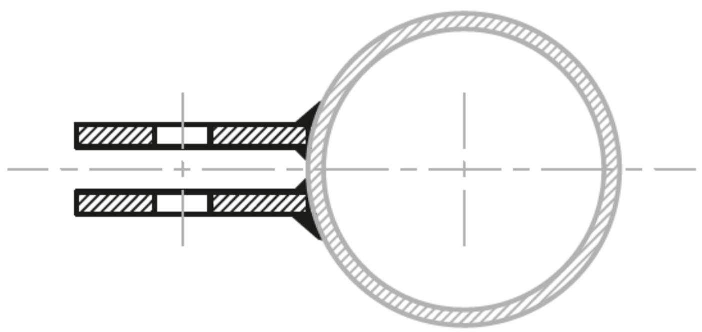
$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1.0$$

$V_{Ed} = 64,47kN$

$$V_{c,Rd} = \frac{A_f \cdot (f_y / \sqrt{3})}{\gamma_{M0}} = \frac{2 \cdot 2 \cdot 46 \cdot 10 \cdot (235/\sqrt{3})}{1,0} = 249,6kN$$

$$\frac{V_{Ed}}{V_{c,Rd}} = \frac{64,47}{249,6} = 0,258$$





Section A-A

9.4 Weld check w4

Weld resistance check

$$F = 47,47kN \qquad a = 3mm \qquad l = 215mm$$

$$\beta_w = 0.8 \text{ for} \rightarrow \text{S235} \qquad \gamma_{M2} = 1,25$$

$$F_u = 360N / mm^2$$

$$\sqrt{\left(\sigma^2 + t^2\right)} \leq \frac{f_u}{\beta_u \cdot \gamma_{M2} \cdot \sqrt{3}}$$

$$\sigma = \frac{M}{W_{el,w}} + \frac{F_v}{A_w} = \frac{F \cdot 24}{4 \cdot 3 \cdot \frac{215^2}{6}} + \frac{F \cdot \cos 26}{4 \cdot 3 \cdot 215} = 28,86N / mm^2$$

$$t = \frac{F_h}{A_W} = \frac{F \cdot \cos 64}{4 \cdot 3 \cdot 215} = 8,07N / mm^2$$

$$\sqrt{\left(28,86^2 + 8,07^2\right)} \leq \frac{360}{0,8 \cdot 1,25 \cdot \sqrt{3}} \rightarrow 29,97 \leq 207,85N / mm^2$$

Shear resistance check

$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1.0$$

$$V_{Ed} = 47,47kN$$

$$V_{c,Rd} = \frac{A_f \cdot \left(f_y / \sqrt{3}\right)}{\gamma_{M0}} = \frac{2 \cdot 2 \cdot 46 \cdot 10 \cdot \left(235 / \sqrt{3}\right)}{1,0} = 249,6kN$$

$$\frac{V_{Ed}}{V_{c,Rd}} = \frac{47,47}{249,6} = 0,19$$

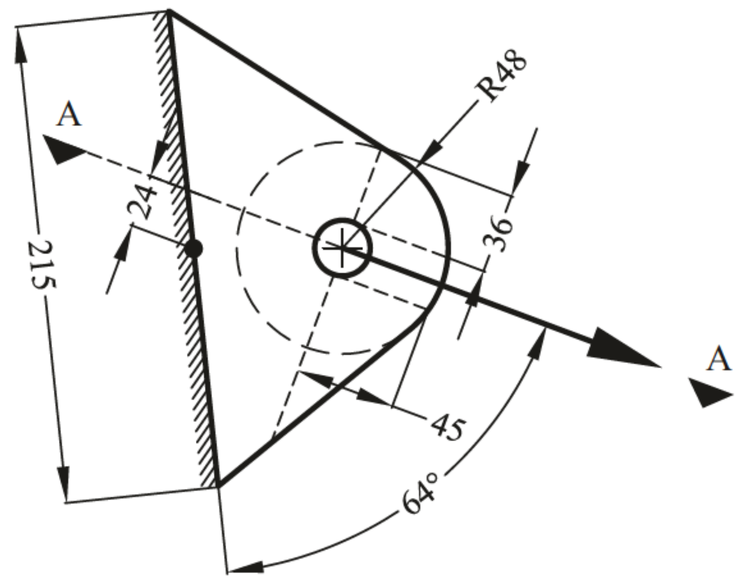
Tension resistance check

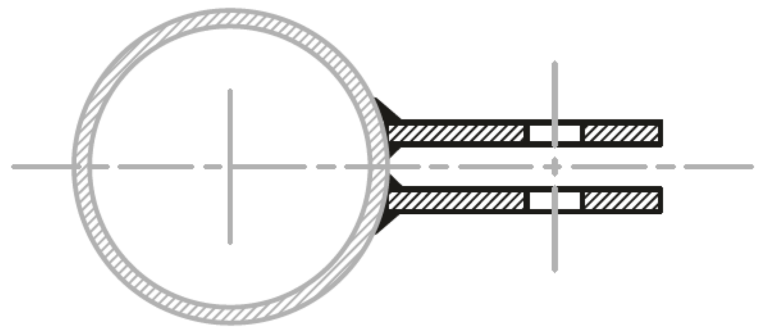
$$\frac{N_{Ed}}{N_{t,Rd}} \leq 1,0$$

$$N_{Ed} = 47,47kN$$

$$N_{t,Rd} = \frac{A_f \cdot f_y}{\gamma_{M0}} = \frac{2 \cdot 2 \cdot 36 \cdot 10 \cdot 235}{1,0} = 338kN$$

$$\frac{N_{Ed}}{N_{t,Rd}} = \frac{47,47}{338} = 0,14$$





Section A-A

9.5 Weld check w5

Weld resistance check

$F = 47{,}47kN \quad a = 3mm \quad l = 297mm$

$\beta_w = 0.8 \text{ for} \rightarrow \text{S235} \quad \gamma_{M2} = 1{,}25$

$F_u = 360 N / mm^2$

$$\sqrt{(\sigma^2 + t^2)} \leq \frac{f_u}{\beta_u \cdot \gamma_{M2} \cdot \sqrt{3}}$$

$$\sigma = \frac{M}{W_{el,w}} + \frac{F_v}{A_w} = \frac{F \cdot 25}{4 \cdot 3 \cdot \frac{297^2}{6}} + \frac{F \cdot \cos 75}{4 \cdot 3 \cdot 297} = 10{,}18 N / mm^2$$

$$t = \frac{F_h}{A_W} = \frac{\cos 15 \cdot F}{4 \cdot 3 \cdot 297} = 12{,}87 N / mm^2$$

$$\sqrt{(10{,}18^2 + 12{,}87^2)} \leq \frac{360}{0{,}8 \cdot 1{,}25 \cdot \sqrt{3}} \rightarrow 16{,}41 \leq 207{,}54 N / mm^2$$

Tension resistance check

$$\frac{N_{Ed}}{N_{t,Rd}} \leq 1{,}0$$

$N_{Ed} = 47{,}47kN$

$$N_{t,Rd} = \frac{A_f \cdot f_y}{\gamma_{M0}} = \frac{2 \cdot 2 \cdot 35 \cdot 10 \cdot 235}{1{,}0} = 329kN$$

$$\frac{N_{Ed}}{N_{t,Rd}} = \frac{47{,}47}{329} = 0{,}144$$

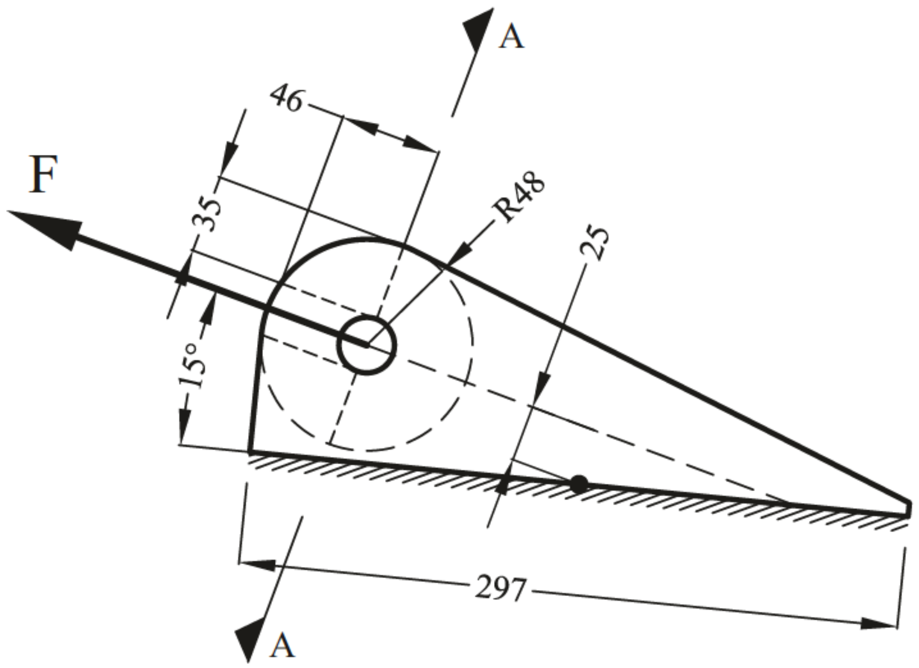
Shear resistance check

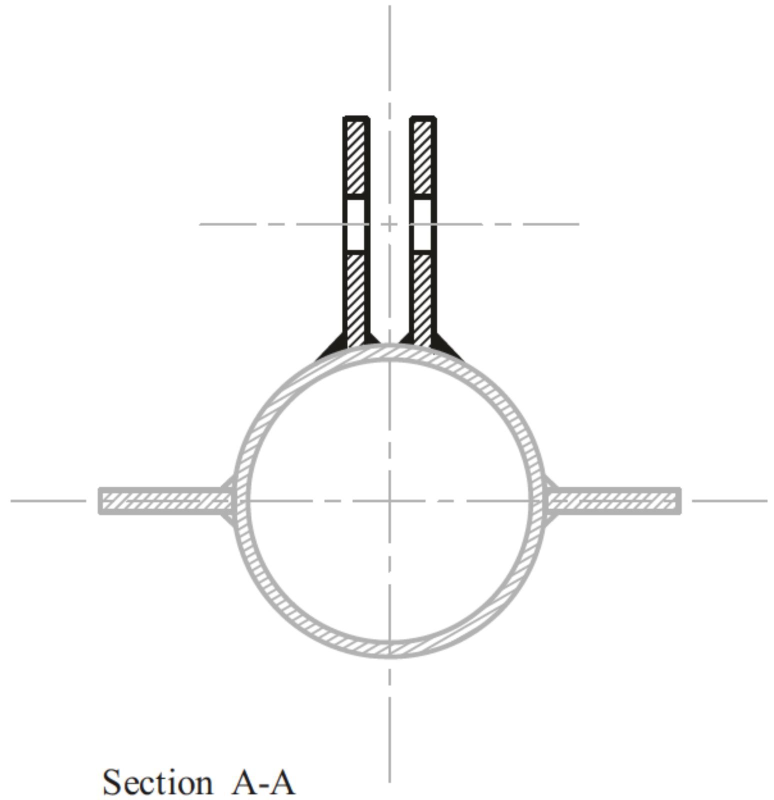
$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1.0$$

$V_{Ed} = 47{,}47kN$

$$V_{c,Rd} = \frac{A_f \cdot \left(f_y / \sqrt{3}\right)}{\gamma_{M0}} = \frac{2 \cdot 2 \cdot 46 \cdot 10 \cdot \left(235 / \sqrt{3}\right)}{1{,}0} = 249{,}6kN$$

$$\frac{V_{Ed}}{V_{c,Rd}} = \frac{47{,}47}{249{,}6} = 0{,}19$$





Section A-A

9.6 Weld check w6

Weld resistance check

$F = 50,05kN \quad a = 4mm \quad l = 70mm$

$\beta_w = 0.8 \text{ for} \rightarrow \text{S235} \quad \gamma_{M2} = 1,25$

$F_u = 360N / mm^2$

$$\sqrt{(\sigma^2 + t^2)} \leq \frac{f_u}{\beta_u \cdot \gamma_{M2} \cdot \sqrt{3}}$$

$$\sigma = \frac{M}{W_{el,w}} \rightarrow \frac{F \cdot 13}{2 \cdot 4 \cdot \frac{70^2}{6}} = 99,49N / mm^2$$

$$t = \frac{F}{A_W} = \frac{50,05}{2 \cdot 4 \cdot 70} = 89,38N / mm^2$$

$$\sqrt{(99,49^2 + 89,38^2)} \leq \frac{360}{0,8 \cdot 1,25 \cdot \sqrt{3}} \rightarrow 133,74 \leq 207,85N / mm^2$$

Cable resistance check

$F_{R,d} \geq Q_{s,d}$

$$F_{R,d} \geq \frac{F_{u,k}}{1,5 \cdot \gamma R}$$

$F_{R,d}$: Tension resistance

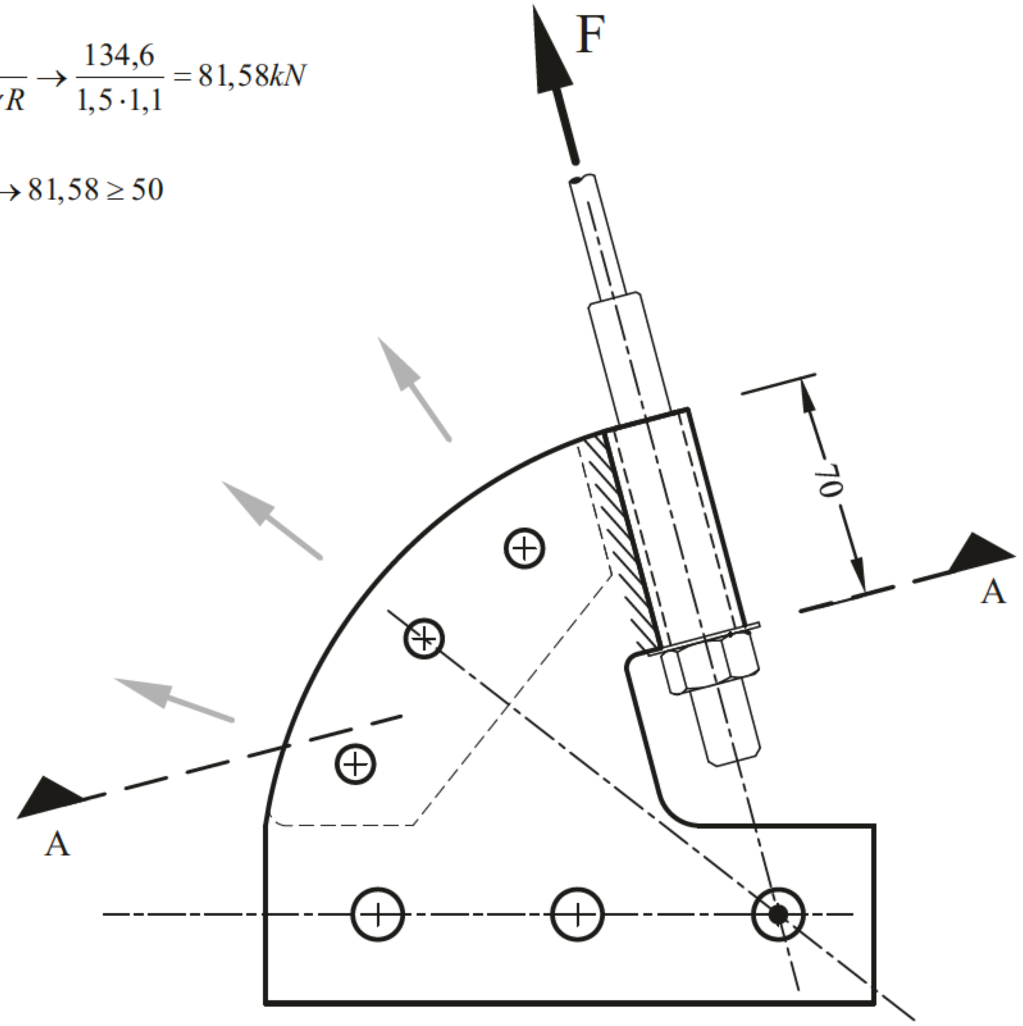
$Q_{s,d}$: Design load $\rightarrow 50kN$

$F_{u,k}$: Characteristic tensile strength $\rightarrow 134,6kN$

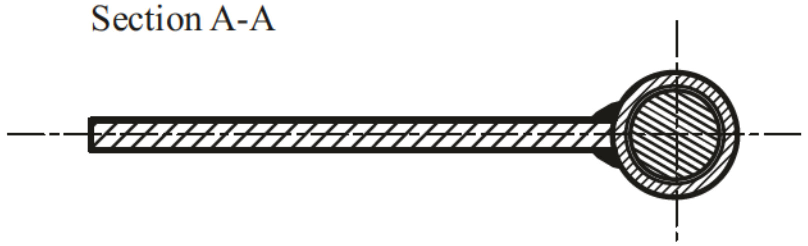
γR : Safety factor $\rightarrow 1,1$

$$F_{R,d} \geq \frac{F_{u,k}}{1,5 \cdot \gamma R} \rightarrow \frac{134,6}{1,5 \cdot 1,1} = 81,58kN$$

$F_{R,d} \geq Q_{s,d} \rightarrow 81,58 \geq 50$



Section A-A



9.7 Pin ended truss bolt and weld check

Bolt shear resistance

$F_{Ed} \le F_{v,Rd}$

$$F_{v,Rd} = \frac{\alpha_v \cdot f_{ub} \cdot A}{\gamma_{M2}}$$

$F_{Ed}: 64,47kN$ Bolt : 8.8 24mm $f_{ub}: 800N/mm^2$

$A: 452mm^2$ $\gamma_{M2}: 1,25$ $\alpha_v: 0,6$

$$F_{v,Rd} = \frac{\alpha_v \cdot f_{ub} \cdot A}{\gamma_{M2}} \rightarrow F_{v,Rd} = \frac{0,6 \cdot 800 \cdot 452 \cdot 2}{1.25} = 347kN$$

$F_{Ed} \le F_{v,Rd} \rightarrow 64,47 \le 347$

Bolt bending resistance

$a: 10mm$ $b: 15mm$ $c: 1mm$

$$M_{Ed} = \frac{F_{Ed}}{8} \cdot (b + 4c + 2a) \rightarrow M_{Ed} = \frac{64,47}{8} \cdot (15 + 4 \cdot 1 + 2 \cdot 10) = 314kNmm$$

$$M_{Rd} = 1,5 \cdot W_{el} \cdot f_{yp} / \gamma_{M0} \rightarrow M_{Rd} = 1,5 \cdot 1357 \cdot 0,64 / 1,0 = 1303kNmm$$

$$\left(\frac{M_{Ed}}{M_{Rd}}\right)^2 + \left(\frac{F_{V,Ed}}{F_{V,Rd}}\right)^2 \le 1 \rightarrow \left(\frac{314}{1303}\right)^2 + \left(\frac{64,47}{174}\right)^2 = 0,195 \le 1$$

Pin ended truss geometrical requirements check

$a = 30mm$ $c = 30mm$ $d_0 = 25mm$ $t = 15mm$

$$a \ge \frac{F_{sd} \cdot \gamma_{M0}}{2 \cdot t \cdot f_y} + \frac{2 \cdot d_0}{3} \rightarrow \frac{64470 \cdot 1,0}{2 \cdot 10 \cdot 236} + \frac{2 \cdot 25}{3} = 30,38 \rightarrow 30 \ge 30,38$$

$$c \ge \frac{F_{sd} \cdot \gamma_{M0}}{2 \cdot t \cdot f_y} + \frac{d_0}{3} \rightarrow \frac{64470 \cdot 1,0}{2 \cdot 10 \cdot 236} + \frac{25}{3} = 22,05 \rightarrow 30 \ge 22,05$$

$$t \ge 0,7 \cdot \left(\frac{F_{sd} \cdot \gamma_{M0}}{f_y}\right)^{1/2} = 11,59 \rightarrow 15 \ge 11,59$$

$$d_0 \le 2,5 \cdot t \rightarrow 2,5 \cdot 15 = 37,5 \rightarrow 25 \le 37,5$$

Weld shear resistance check

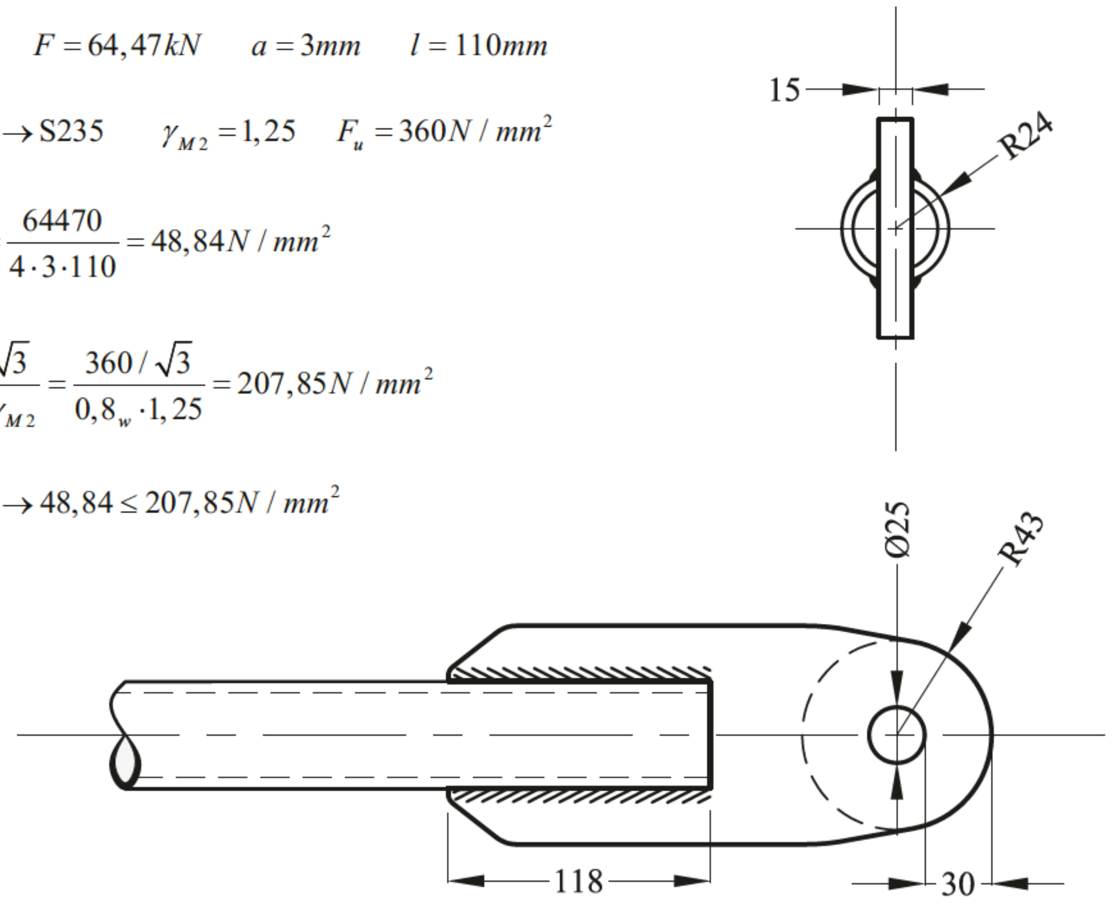
$V_{w,Ed} \le V_{w,Rd}$ $F = 64,47kN$ $a = 3mm$ $l = 110mm$

$\beta_w = 0.8$ for $\rightarrow$ S235 $\gamma_{M2} = 1,25$ $F_u = 360N/mm^2$

$$V_{w,Ed} = \frac{F}{A_w} = \frac{64470}{4 \cdot 3 \cdot 110} = 48,84N/mm^2$$

$$V_{w,Rd} = \frac{f_u \cdot \sqrt{3}}{\beta_w \cdot \gamma_{M2}} = \frac{360/\sqrt{3}}{0,8_w \cdot 1,25} = 207,85N/mm^2$$

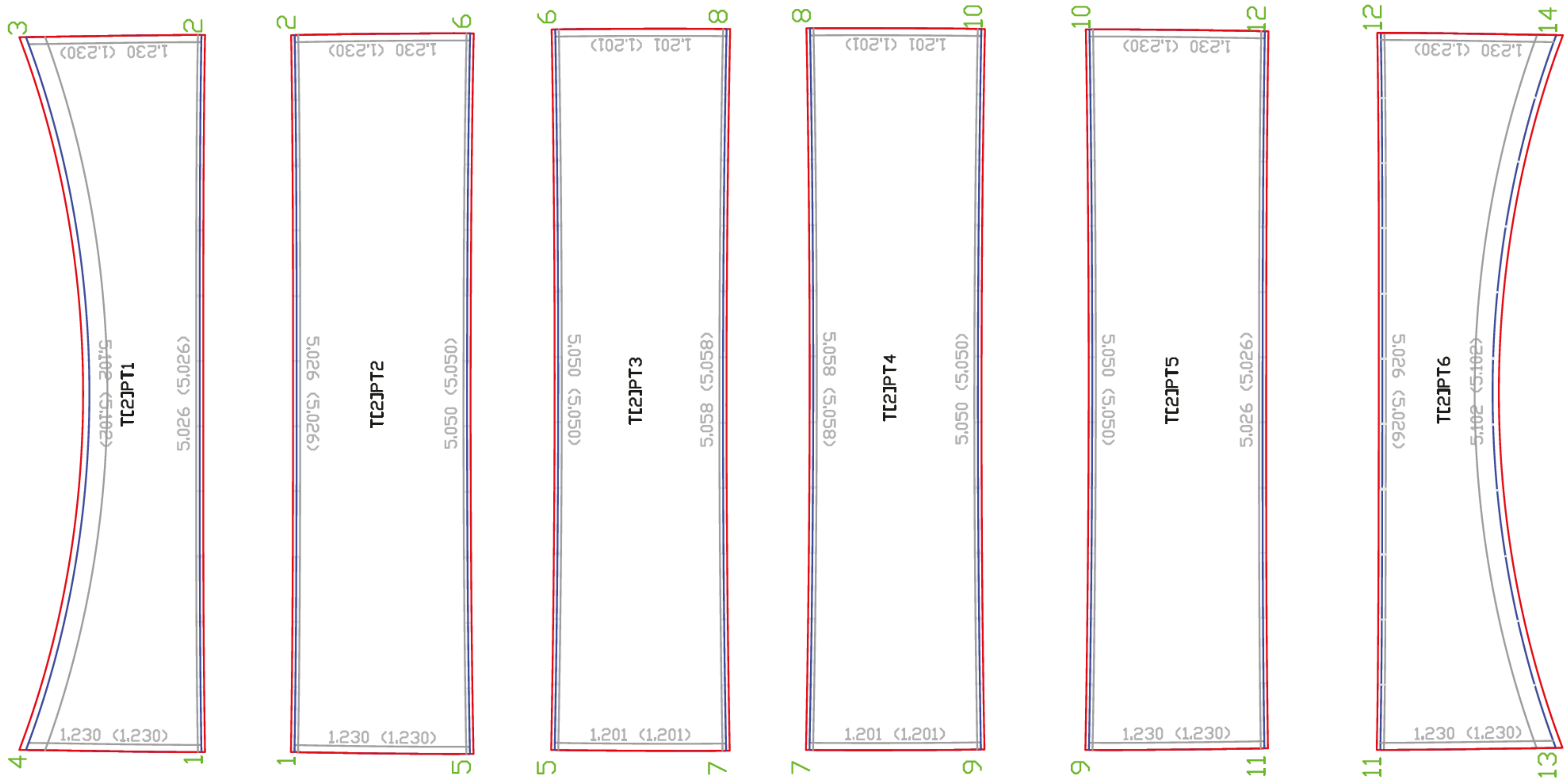
$V_{w,Ed} \le V_{w,Rd} \rightarrow 48,84 \le 207,85N/mm^2$



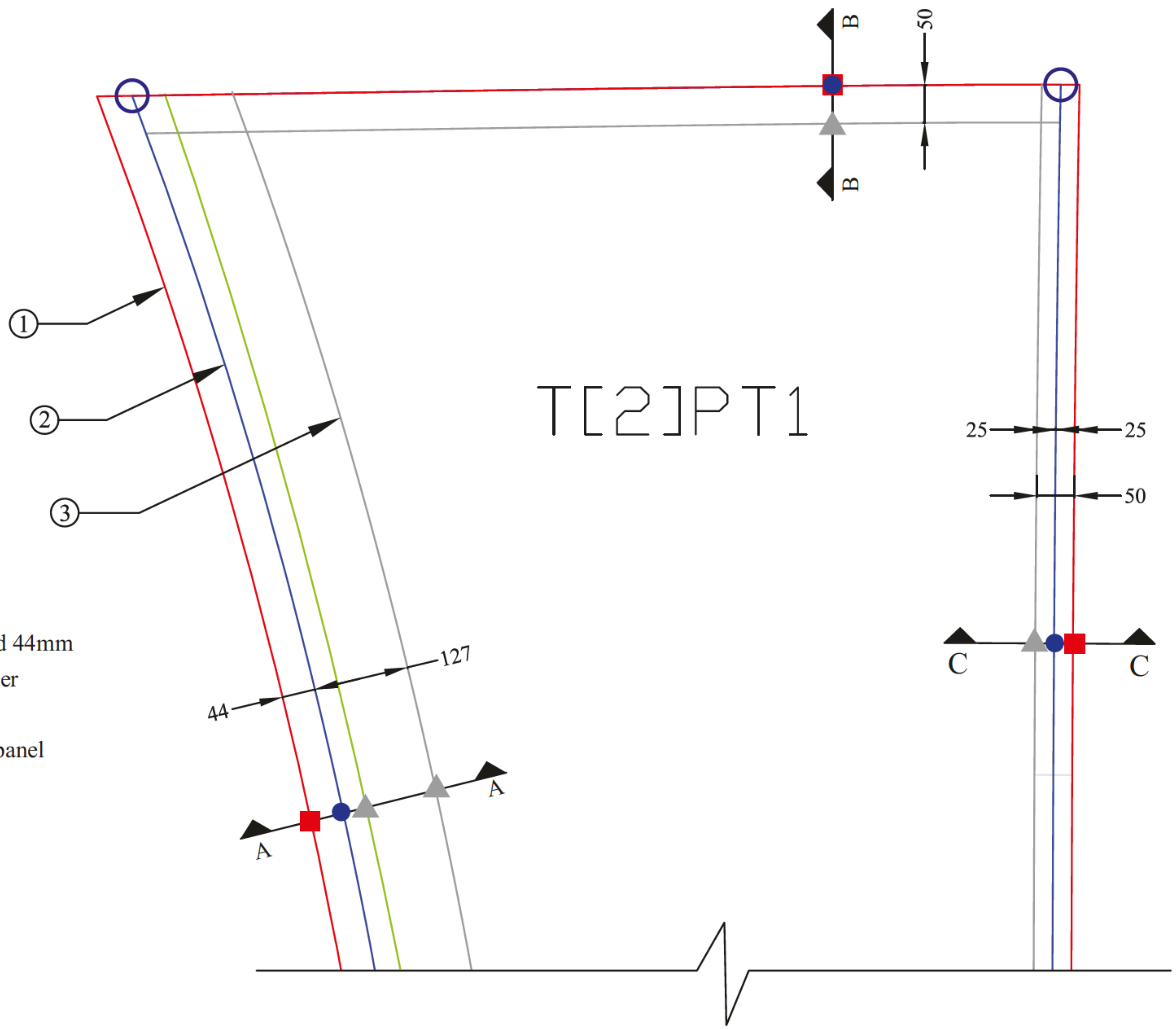
Membrane surface details

10.1 Membrane patterning details

Cutting line (Membrane cutting track, final border)
System line (Membrane original patterning track)
Offset line (Where membrane overlapping start point track for welding helper)



10.2 Panel manufacturing details



- 1- Cutting line - Membrane was extended 44mm
- 2- System line - Membrane original border
- 3- Offset line - Welding helper lines
- 4- System point - Original corner of the panel

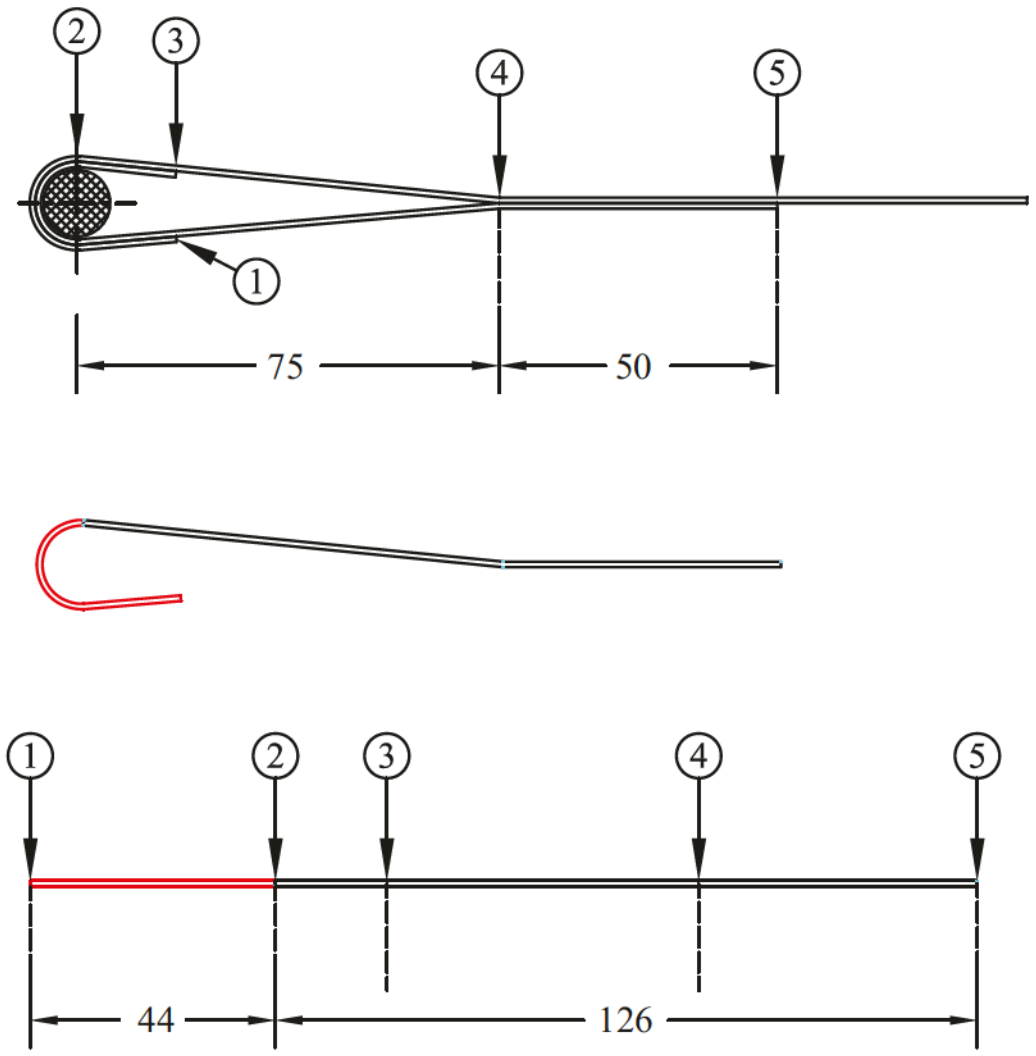
A-A Section - Cable pocked detail
B-B Section - Rigid edge detail
C-C Section - Panel welding detail

All dimensions are in unit mm.

10.3 Membrane welding details

Section A-A

Flexible edge cable pocket details

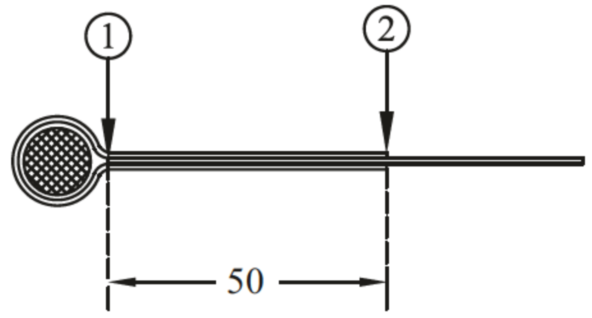


1- Cutting line
2- System line
3- Welding start point (It will be drawn bottom side of the membrane)
4- Welding end point (Not need offset line)
5- Welding start point (It will be drawn bottom side of the membrane)

All dimensions are in unit mm.

Section B-B

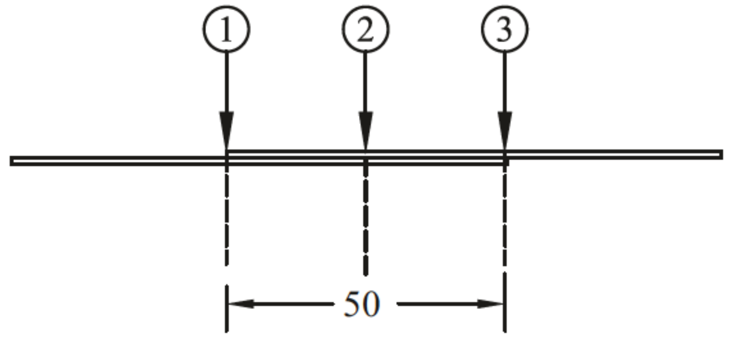
Rigid edge welding detail



1- System line - Cutting line
2- Offset line (Welding start point)

Section C-C

Typical membrane panel inside welding detail



1- Offset line (Welding start point)
2- System line
3- Cutting line

Appendix

A.1 Numerical form-finding example and historical background

Frei Otto became internationally known with the Expo 1967 Montreal German Pavilion project. This structure was the largest project ever realized by Otto at that time. This project, which consists of a PVC/PES membrane roof that hanged on to the cable-net construction from inside, was cover an area 8.000m². The stresses on the cables were calculated on the physical model which scaled 1/175. This structure was prepared for use only one summer but was used for 6 years. This cable-net structure was lead for the 1972 Munich Olympic Stadium project.[KN] The Munich Olympic Stadium project is one of the earliest examples of tensile roof systems. This project is an outstanding architectural and engineering success of its term. In addition, this project demonstrates the transition from physical modeling to numerical modeling in determining the initial geometry and structural behavior of tensile structures.[LW], [DG]

When the Expo 67 Montreal German Pavilion project was realized, there was no numerical method for designing and analyzing the tensile structures. At that time, the only way to produce such a structural system was the physical modeling.[GR] The design of the Expo 67 cable-net project was based on scale models made from soap films and elastic fabrics. In the design process, a series of precision models were prepared to ensure that the manually measured surface geometry can be used for static analysis and production. A prototype of a part of the structure was produced to check the reliability of measurements coming from these precision scaled physical models.[LW] This prototype is still being used at the Institute for Lightweight Structures and Conceptual Design (ILEK) at the University of Stuttgart (2015).[KN], [DC]

Otto produced a sensitive physical model to provide all the necessary information for the Munich Olympic Stadium project. Klaus Linkwitz proposed using the photogrammetry method to describe the three-dimensional geometry of the surface without touching to the physical model. This method allows the precise measurement of the surface using photographs of the three-dimensional surface. When photogrammetry method was applied to the physical model of stadium, it was understood that the prepared physical model was not enough sensitive to producing the cutting patterns of the cable-net surface.[GR] When determining the cable-net dimensions of the real project from the scaled model, a systematic inaccuracy about 1mm was bringing large measuring problems in total. Therefore, a new measurement method had to be developed.

Linkwitz has made a significant contribution to the form-finding process of the Munich Olympic Stadium cable-net roof. The key role at this project was the Force Density Method, which he was developed along with his doctoral student H.J. Schek, in 1969. This method allowed the initial geometry of the cable-nets to be determined in a linear way without taking into account the mechanical properties of the material. Linkwitz achieved this by defining a new mechanical variable called force density. This ingenious idea became the most simple and powerful form-finding method.[KW] Later, Linkwitz generalized the method to grid-shells and timber roofs under compression using the inverted design concept.[KW], [WD]

The Force Density Method was developed to respond to the needs of the Munich Olympics project. This method uses linear system equations, depending on the force/length ratio, to determine the static equilibrium state of the prestressed cable-net structure.[LW] The Force Density Method is one of the basic form-finding methods commonly used today.

In a numerical form-finding process, membrane surfaces are modeled as a mesh. The connections nodes are considered as a pinned join. The physical properties and lengths of the line elements forming the surface are not taken into account. The main objective of form-finding process is to reach an equilibrium state for all elements under the desired prestress.

Let's assume that the system consisting of four line elements shown in figure 5.1 is a part of a large mesh surface. In which position of the node **p5**, the system reaches an equilibrium state? The analysis using the Force Density Method was performed here manually, as an example.

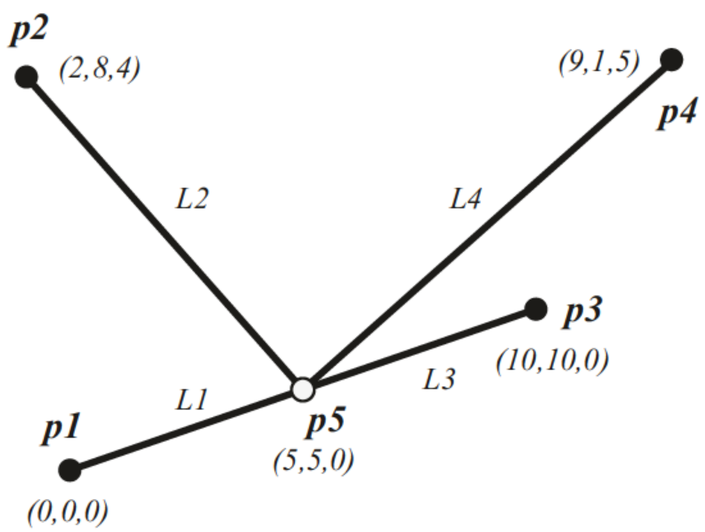


Figure 5.1 Initial condition of the cable-net

Initial tension load of cables

Pretension for L_1 $(S_1) = 6kN$

Pretension for L_2 $(S_2) = 5kN$

Pretension for L_3 $(S_3) = 4kN$

Pretension for L_4 $(S_4) = 7kN$

Force Density Method equilibrium equations

$$\sum F_x = 0 \rightarrow \frac{(x_p - x_1)}{L_1} \cdot S_1 + \frac{(x_p - x_2)}{L_2} \cdot S_2 + \frac{(x_p - x_3)}{L_3} \cdot S_3 + \frac{(x_p - x_4)}{L_4} \cdot S_4 = 0$$

$$\sum F_y = 0 \rightarrow \frac{(y_p - y_1)}{L_1} \cdot S_1 + \frac{(y_p - y_2)}{L_2} \cdot S_2 + \frac{(y_p - y_3)}{L_3} \cdot S_3 + \frac{(y_p - y_4)}{L_4} \cdot S_4 = 0$$

$$\sum F_z = 0 \rightarrow \frac{(z_p - z_1)}{L_1} \cdot S_1 + \frac{(z_p - z_2)}{L_2} \cdot S_2 + \frac{(z_p - z_3)}{L_3} \cdot S_3 + \frac{(z_p - z_4)}{L_4} \cdot S_4 = 0$$

The form-finding process for iteration-1 is below. The calculation of other iterations was not repeated here, but the results are in table 5.1.

Iteration-1

1) Length

$$L_1^1=\sqrt{(5-0)^2+(5-0)^2+(0-0)^2}=7{,}071$$

$$L_2^1=\sqrt{(5-2)^2+(5-8)^2+(0-4)^2}=5{,}831$$

$$L_3^1=\sqrt{(5-10)^2+(5-10)^2+(0-0)^2}=7{,}071$$

$$L_4^1=\sqrt{(5-9)^2+(5-1)^2+(0-5)^2}=7{,}55$$

q=S / L

q: Force density value

S: Applied load (prestress)

L: Length

2) Force density values

$$q_1^1=\frac{6}{7{,}071}=0{,}849 \qquad q_2^1=\frac{5}{5{,}831}=0{,}857 \qquad q_3^1=\frac{4}{7{,}071}=0{,}566 \qquad q_4^1=\frac{7}{7{,}55}=0{,}927$$

3) New coordinates of node p5

X coordinate

$$(x_p-x_1)\cdot q_1+(x_p-x_2)\cdot q_2+(x_p-x_3)\cdot q_3+(x_p-x_4)\cdot q_4=0$$

$$(x_p^1-0)\cdot 0{,}849+(x_p^1-2)\cdot 0{,}857+(x_p^1-10)\cdot 0{,}566+(x_p^1-9)\cdot 0{,}927=0\rightarrow x_p^1=4{,}913$$

Y coordinate

$$(y_p-y_1)\cdot q_1+(y_p-y_2)\cdot q_2+(y_p-y_3)\cdot q_3+(y_p-y_4)\cdot q_4=0$$

$$(y_p^1-0)\cdot 0{,}849+(y_p^1-8)\cdot 0{,}857+(y_p^1-10)\cdot 0{,}566+(y_p^1-1)\cdot 0{,}927=0\rightarrow y_p^1=4{,}202$$

Z coordinate

$$(z_p-z_1)\cdot q_1+(z_p-z_2)\cdot q_2+(z_p-z_3)\cdot q_3+(z_p-z_4)\cdot q_4=0$$

$$(z_p^1-0)\cdot 0{,}849+(z_p^1-4)\cdot 0{,}857+(z_p^1-0)\cdot 0{,}566+(z_p^1-5)\cdot 0{,}927=0\rightarrow z_p^1=2{,}52$$

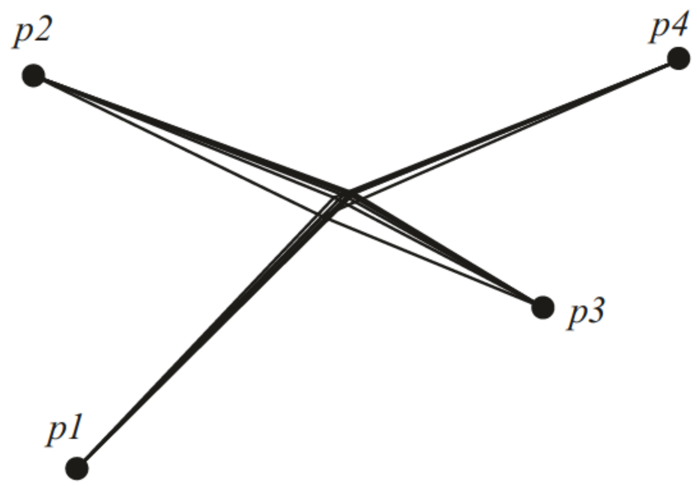


Figure 5.2.a Displacement of elements

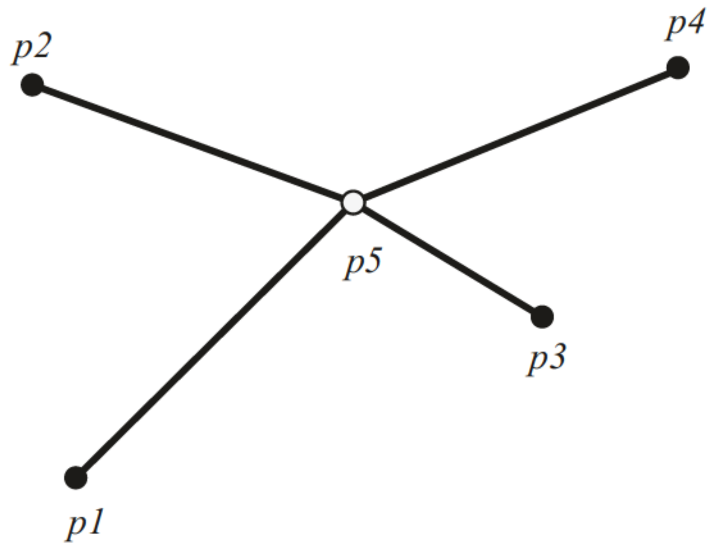


Figure 5.2.b Equilibrium location of the node **p5** after 7 iteration.

	p5 x	p5 y	p5 z	L1	L2	L3	L4	q1	q2	q3	q4	S1	S2	S3	S4
Initial	5,0	5,0	0,0	7,071	5,831	7,071	7,55	0,849	0,857	0,566	0,927	6	5	4	7
Iteration 1	4,913	4,202	2,52	6,939	5,01	8,114	5,754	0,865	0,998	0,493	1,217	5,891	4,294	4,593	5,334
Iteration 2	5,004	3,955	2,82	6,974	5,175	8,334	5,427	0,86	0,966	0,48	1,29	6,033	5,165	4,109	6,605
Iteration 3	5,101	3,843	2,868	7,001	5,308	8,375	5,275	0,857	0,942	0,478	1,327	6,021	5,128	4,02	6,805
Iteration 4	5,163	3,786	2,887	7,023	5,385	8,378	5,191	0,854	0,929	0,477	1,348	6,019	5,073	4,005	6,888
Iteration 5	5,2	3,756	2,898	7,039	5,428	8,392	5,143	0,852	0,921	0,477	1,361	6,011	5,043	4,003	6,933
Iteration 6	5,223	3,738	2,905	7,049	5,454	8,395	5,114	0,851	0,917	0,476	1,369	6,006	5,023	4,004	6,960
Iteration 7	5,235	3,727	2,91	7,054	5,469	8,398	5,097	0,851	0,914	0,476	1,373	6,003	5,015	3,997	6,978

Table 5.1 Form-finding process iteration results

After 7 iterations, the system is not converged completely yet, it needs several times new iteration.

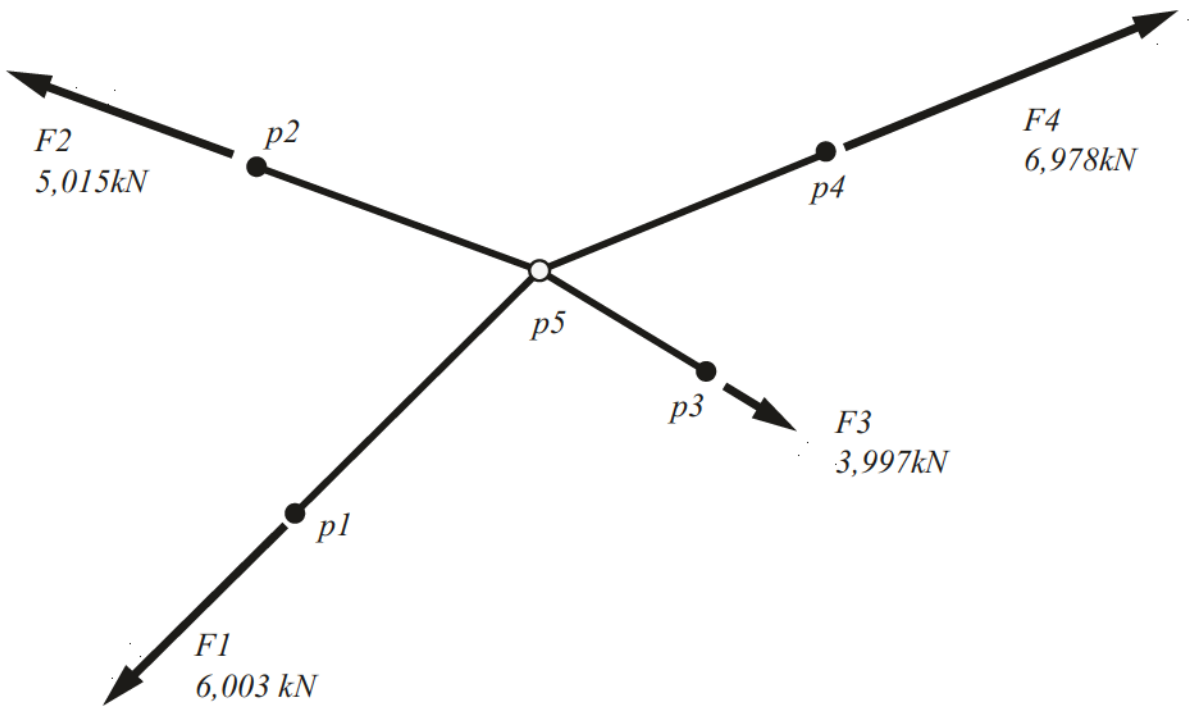


Figure 5.3.a The reactions with iteration 7

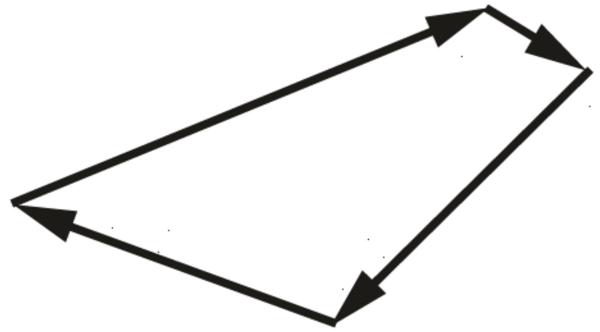


Figure 5.3.b The equilibrium of vectors

$$\sum F_X = 0 \rightarrow \frac{(5,223-0)}{7,049}\cdot 6,003 + \frac{(5,223-2)}{5,454}\cdot 5,015 + \frac{(5,223-10)}{8,395}\cdot 3,997 + \frac{(5,223-9)}{5,114}\cdot 6,978 = 0,017$$

$$\sum F_Y = 0 \rightarrow \frac{(3,738-0)}{7,049}\cdot 6,003 + \frac{(3,738-8)}{5,454}\cdot 5,015 + \frac{(3,738-10)}{8,395}\cdot 3,997 + \frac{(3,738-1)}{5,114}\cdot 6,978 = 0,019$$

$$\sum F_Z = 0 \rightarrow \frac{(2,905-0)}{7,049}\cdot 6,003 + \frac{(2,905-4)}{5,454}\cdot 5,015 + \frac{(2,905-0)}{8,395}\cdot 3,997 + \frac{(2,905-5)}{5,114}\cdot 6,978 = 0,009$$

The results were checked with Force Density Method equilibrium equation.

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