Membrane Materials and Membrane Structures in Architecture

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Abstract

Membrane structures are hugely popular in architectural design and are increasing in their abundance within buildings. There is an increasing trend concerning the use of membrane structures within architectural design. It is important to recognize the reasoning behind the growth in popularity: why are so many architects starting to use the design feature within their designs? The features of the membrane structure have been provided; an analysis of the strengths and weaknesses provides strength to the reasoning behind its use. This dissertation examines a variety of different factors concerning the membrane structures. It provides a detailed study of the use of membrane structures within building design; additionally, all of the different contributory factors have been referenced, such as the structural components and mechanical usages.

Much primary and secondary research has been referenced to illustrate the breadth of the topic. Membrane structures have been used in architecture for over 50 years; therefore, there is a large back catalogue of research papers that focus on them. The dissertation follows a case study structure and uses 12 examples of membrane structures within architecture. Each case study provides a real-life example of how membrane structures have been successfully applied to modern day architecture. Additionally, it examines the complexity behind the construction of membrane structures and materials. It is important to understand the structural components that make it so appealing to architects. The associated advantages and disadvantages of membrane materials have been examined. Furthermore, the relationship between the construction components and the integrated design has been mentioned. All of these factors provide a strong understanding behind the use of membrane structures, explaining how they can be used and why they are becoming so popular.
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References
Chapter 1: Introduction

Membrane structures are one form of architectural feature that are becoming hugely popular within modern day engineering. They are becoming majorly prominent in many designs. Although they have been used in architecture for over 50 years, their use as an aesthetic and ergonomic feature is becoming more apparent. Much of society is unaware of the detailed specification behind the membrane structures. The complexity of the construction process, involving all of its contributory materials, is unknown to many people within the industry.

This thesis has been based on much research surrounding the topic of membrane structures and contributory membrane materials within architectural design. These factors have been closely examined and thoroughly researched to discover results that lead to a valid conclusion. 12 different examples of membrane structures within architectural design have been used in this piece of research. The dissertation follows a case study methodology; this allows for deep examination and understanding regarding few individual examples.

The design of this dissertation has been structured around three main research points; each research point examines a variety of different features concerning different levels of membrane structure design.

1) Characteristics of membrane design (8 marks) – studies the different features of typical membrane structure design, including all of the factors that contribute towards its appeal to architects. Standard features of membrane structures include a larger span across the building surface, giving it a broad use of applications. Uses may include covering art exhibitions or music event venues. From an economic perspective, they are highly energy-efficient and save much money on transportation costs. The design can be easily deconstructed and transported to different areas. Furthermore, they are widely
renowned as being highly safe and reliable. From an aesthetic perspective, they are considered to be very attractive and stylish, especially with modern day architecture.

2) Basic properties of membrane materials (2 marks) – studies the elements behind the structural components of membrane materials. This section examines the composition of the materials used in the construction process. Furthermore, it studies the different properties that the construction process provides to the building; the benefits of the membrane structure and its contribution to the building specification will be referenced.

3) Study the mechanics behind the joint node within the membrane structure (2 marks) – studies the mechanical features of the joint node, specifically within the membrane structure design. The design principals of the joint node would be referenced, explaining the different methods of design. Additionally, the variety of membrane structure forms will be examined; this allows for a close examination of the relationship between the joint node and the membrane structure.

As previously discussed, this dissertation follows a rigid structure. A detailed review of all the complimentary literature will be provided, which references the many other studies that examine this topic. Next, details about the 12 case studies shall be given, providing weight to the research paper. After, an analysis of the case studies shall be undertaken, closely examining the differences between each example. Finally, there will be a conclusion that summarizes the findings of the research paper.
Chapter 2: Literature Review

2.1. Introduction

A German designer by the name of Professor Frei Otto amazed architects from around the world with his design of the Pavilion of the Federal Public of Germany for the EXPO held in 1967 (Roy, 1967). At the time it was standard to observe structures composed of steel and glass. Professor Frei’s membrane structure was lightweight, slim and soft which provided something new and fresh to the architectural field. His design was also very different from any other designs at the time, as he used curved surface areas which were made brighter due to the translucency of the membrane material.

Membrane structures that closely resemble tent like structures came from Germany. These were sturdy and reliable structures that quickly came to form a vital aspect of modern day architecture which quickly spread across the globe. Even in present times these structures are still regarded as very reliable and still well suited to specific types of structures.

2.2. The history of membrane structures

In an essay he wrote in 1961, Professor Otto argued that buildings should not be viewed or designed as fixed structures into which people can be squeezed into. He further put forward his viewpoint that buildings should grow along with us, and be renovated in such fashion. Otto stated that the minimal structural material developed through extensive research was also present in the natural environment, and that it was possible to utilize properties present within organists to produce aspects of the membranes. (Koch, 2004).
Otto reminded the world that although tents had been in existence for over 30,000 years and are considered as easy to construct, they are in fact extremely difficult to structure correctly and that precise tent construction is among the most difficult methods of construction.

Otto and his colleagues published an article in 1965 known as Spannweiten, which detailed all of their findings in the research of membranes structures from an architectural perspective. This paper received attention from academics and experts in the field from across the globe. Otto went on to work with other experts at the institute for Lightweight structures where advancements in technology were made. These advancements were put into practice when the German Pavilion was constructed for the 1967 Expo in Montreal (Roy, 1967). This building went on to significantly shape the world’s knowledge of membrane structures and symbolized the latest advancements in this technology across the globe.

The 1970 Expo was held in Japan. Rather than use structural forms traditional to Japan, the architects decided to use membrane structures for many of the constructions. Although the Expo showcased the reliable potential of the membrane structures, they were not widely favored until many years later (HeeKyun, 2005).

Numerous designs for membrane structures were put forward for The USA’s entry for the 1970 Expo. David Geiger’s design was accepted as it was seen as more realistic as well as aesthetically pleasing to the eye. His idea was to use a low profile air supported membrane for the structure of the US Pavilion.

The US Pavilion was required to meet safety standards and therefore it was designed so that in the event that the membrane structure did deflate, it would not intrude on the spectators seating area or the field. This design was hailed as
further advancement in the development of membrane structures that potentially allowed the development of air domes. Future air dome structures used the US Pavilion as a model for their designs.

From 1970 it was the USA that led the way in terms of research and investment into membrane structures. This paid dividends as Geiger Berger associates made many new developments within the technology throughout the 1970’s. One such development was the use of PTFE coated glass fiber membrane as a new membrane material. This material made it possible to construct enduring, fixed membrane structures throughout the USA (Brown, 2001).

Famous early air dome structures in the USA were the Steve Lacy Field House at Milligan College which was built in 1974 and the Thomas E. Leavey Activities Center at Santa Clara University which was built in 1976. These were hailed throughout the USA as brilliant designs fit for purpose, and it was these buildings which sparked a high demand throughout the USA for air dome structures to be built (Mewes, 1993). Entertainment and stadiums were hugely popular in the USA and they wanted these Domes to protect them against all types of weather and to be capable of hosting a large capacity of people. One example of these stadiums that successfully utilized this technology was the Silver Dome of Pontiac city which was constructed to be able to seat 80,000 spectators.

Before the construction of these air Domes, large scale spaces were associated with negative characteristics such as shadowy and stuffy. However, this all changed with membrane structures which made it possible for light to spread around the entire complex. Another great advantage of the membrane structures is that they could be constructed very economically, which is why they grew so rapidly throughout the USA (Mewes, 1993). However, membrane structures used for air domes were not without their problems. There were a significant number of structural accidents, the costs associated with continual inflation was high and
it was complicated to control the inflation pressure. As such in the 1980’s, alternative viable structural techniques began to be investigated.

By the mid 1980’s membrane structures were not just used to make spaces bigger, but they had evolved to combine beauty with unique structural forms. Buildings using this evolved technique included the Lindsay Park sports center built in 1984 and the Chene Park Amphitheater built in 1990. Additionally, membrane structure also began to be mixed with glass in order to generate bright filled spaces (Kaltenbach, 2004). This technique was particularly prevalent in shopping malls.

The air dome as the dominant structure in the USA was replaced towards the end of the 1980’s by the tensegrity dome which used an efficient system of cables and posts to securely cover large spaces. Examples of buildings utilizing this new method at the time included the Redbird Arena constructed in 1988, the thunder dome constructed in 1989 and the Georgia dome constructed in 1992. In addition, designed by Geiger Associates, the Gymnastics Hall and the Fencing Hall in the complex where the 1986 Seoul Olympics were held also utilized this new system of construction (Happold, 2009).

Architects took membrane structures into Europe in the mid 1980’s which again strengthened the advancements in the field, as the Europeans had new ideas and created unique structures as opposed to the structures in the USA which were all quite similar in design. The first such structure to materialize in Europe was the Schlumberger Cambridge Research Center built in 1985. However, it was not until 1989 when the Nuage Leger was attached to the Grande Arche in Paris did this style of construction really impress in Europe. The Nuage Leger was an impressive membrane structure which took the shape of floating clouds.

European football stadiums such as the Rome Olympic Stadium constructed in
1990 began to use membrane structures due to their advantageous features, namely that they were able to filter through natural light, unlike traditional roofs which would actually darken the areas beneath them.

Balanced from a space frame acting as a compression ring, the membrane structure of the Rome Olympic Stadium was a bright roof which utilized a combination of a cable structure and a membrane structure. This was roof was not only visually pleasing to the eye bit it also did not weigh very much compared to structures that were used in the past. Other stadiums such as the San Nicola Stadium built in 1990 and the Gittlieb-Daimler stadium built in 1993 also sought to use membrane structures to produce both beautiful and well lit stadiums with their own blend of creativity (HeeKyun, 2005).

As developments were made in technology, PFTW coated glass fiber fabric came to replace the PVC coated polyester fabric as the material of the membrane structures in Europe (Kaltenbach, 2004).

There was too much replication of membrane structure designs according to Frei Otto, and it was not until alternative framing techniques were developed and that the structures were produced on a greater scale that many individualist and creative form emerged.

Although Japan used membrane structures within the Expo that they hosted in 1970, there was not much demand for these types of structures in the immediate years following this Expo. This was because Japan already had a uniquely aesthetically pleasing design style and because they were not used to constructing suspension structures.

This situation changed quickly in the 1980s as design competitions were hosted in Japan. A lot of the entrees in these competitions provided very imaginative designs utilizing membrane structures and as such numerous amazing structures
utilizing this method began to be developed throughout Japan. As this happened many architects began to realize how advantageous membranes structures could be. Buildings were designed with membrane structures which served to spread light to specific parts of the complex. Additionally, membrane structures allowed indoor crops to be nurtured by the natural light which was filtered through, and as such the position of the these plants were also factored into the blue prints of the structures(HeeKyun, 2005).

Increasingly imitation of structures is become more prevalent around the world. This was due in part to modern technology and the increased speed of communication that this technology allows. When advancements in design are found in one section of the globe, they quickly spread to other parts.

2.3. The role of structural design offices in the design of membrane structures

It is important to be aware of safety issues when utilizing membrane structures. Unlike traditional structures, membrane structures are primarily under tension and have characteristics that set them apart from other forms. When using membrane structures, it is often structural designer who manage the project as in the past, architects who were only familiar with traditional construction have found utilizing membrane structures too difficult(Baker, 2000).

In the USA a company known as Geiger Berger Associates left behind a great legacy and contributed to a number of significant developments and advancement in the field including the introduction of new materials that could be used to construct the membranes. Additionally, the structural techniques that the company produced enabled the framing of large spaces including low profile air supported structures and tensegrity cable dome structures. The Gymnastics Hall
and Fencing Hall for the Seoul Olympics was the first cable dome structure ever produced and was actually designed by the head of the company, David Geiger.

Unfortunately David Geiger passed away in 1989 and Horst Berger left the company to pursue his own projects. He was subsequently involved in the construction of the both the San Diego Convention Center in 1989 and the Passenger Terminal at Denver International Airport in 1994.

As was the case in the USA, structural designers were also required to take the lead when constructing membrane structures in Japan. Demand for membrane structures in Japan significantly increased following the success of the Tokyo dome built in 1988 (Mewes, 1993). The membrane structures which were utilized on other buildings following the Tokyo dome were combined with a traditional Japanese style. This meant that designers were able to use the advantages of membrane structures whilst also making sure that the designs had a Japanese uniqueness and character to them. The Kaio Kogyo Corporation in Japan provided a substantial amount of investment and research into membrane structures which led to many developments within Japan (HeeKyun, 2005). Since then, the firm has gone on to become a group of technical experts who are able to offer support assistance to both structural designers and architects alike.

Structural design offices began to set up in Europe following the wide spread approval of membrane structures. One of the most famous structural design offices internationally was Ove Arup and Partners who went onto design a number of original and creative structures throughout the 20th Century. Involved in major projects throughout Europe such as the Schlumberger Cambridge Research Center and the San Nicola Stadium this office quickly established itself as an expert and front runner in the field of membrane structures, favored by clients for their ability to effectively and creatively express light and shadow within their structures (Mewes, 1993).
Another office known as Schlaich Bergermann and Partners who were involved in the construction of both the Gottlieb-Daimler Stadium and the Weber Center Court achieved recognition in the field due to their ability to create original lightweight membrane structures.

IPL was another office which had just started to become very well known and successful when they were halted due to the unfortunate death of their leader Herald Muhlberger in 1994. This office actually designed the German Pavilion for the 1992 Expo in Seville (Fernandez, 2006).

As more experts came into the field and could support people to have a greater understanding of membrane structures, architects began to experiment with membrane structures and they succeeded in producing constructions which unlocked some of the hidden potential of membrane structures.

2.4. Structure, Construction Method and Membrane Material

A construction that directly utilizes the elements of membrane materials is known as a ‘membrane-structure building’. Either a cable frame or a skeleton frame can form the structure that sustains the membrane. It is possible for a structure on a small scale to consist of the membrane itself as the structural material. However, such a process is not possible on a larger scale structure because the membrane is not strong enough. If used on a large scale construction it is essential for the membrane to be strengthened somehow or used in conjunction with a frame (Smith, 2001).

Membrane materials have enough strength to be directly linked to the main frame unlike other roof materials. A membrane material has a natural tendency to curve,
and although it can endure tension, it cannot withstand compression or bending. It is a complex task to make a curved surface using tension, and the process of designing the membrane structures is dependent on utilizing the tension in a precise fashion (Kaltenbach, 2004).

In the early days it was believed that membrane structures could only be designed with mechanics in mind and that there was no room for creativity in the design. However, it was later discovered that although the curved surface is subject to specific mechanical requirements, there is much room for individualistic touches on the periphery of the surface area. Even so it is important to note that the periphery must still be supported either with cables or a frame.

An architect, who is used to working on traditional structures, may find it helpful to use a skeleton-frame membrane structure when constructing a membrane structure. This is because the membrane is able to be extended over steel, wood or even a reinforced concrete frame in order to shape the space (Herzog, 1996).

Balloons actually provided the inspiration for air inflated membrane structures. Although F.W. Lancheser of England may have been first to put forward the idea for a field hospital, it was the Radar Dome built in the USA in the year of 1946 that was actually the first time that this structure had been created for a building on the ground. Following the success of this dome, similar structures were replicated across the private sector in the USA. As more of these structures were seen, international interest in these structures significantly increased.

It is theorized that the use of membranes as structures were used over 30,000 years ago for the tents used by Nomadic tribes. Since these times, the technology involved with membrane structures has been ever increasing. These days, membrane structures are now as safe and durable as traditional buildings. This is due in part to the materials that form them. Synthetic fibers and glass fibers are
now utilized and coating materials have enabled the structures to contain both water and fire resistant qualities. Advancements have been made and there are many advantages to using membrane structures including their qualities of transparency, low weight and their ability to be applied to frames for large scale spaces. For instance, it is now possible to cover a large space that would not be possible with traditional techniques with just one sheet of membrane material (Kaltenbach, 2004).

However, it must be recognized that membrane materials are not simply suited for all projects. If just one thin sheet is used then it will be difficult to adequately protect it from tearing as well as being difficult to provide insulation for heat and sound.

Advancements in the materials of the membrane structures have been continually been made.

Significant advancements have included the industrialization of PVC in 1933, the development of PTFE in 1938, the industrialization of Polyester fiber in 1947, and finally PTFE coated glass fiber fabric which was developed in 1972 (Mewes, 1993).

PTFE coated glass fiber fabric is considered a fixed long lasting building material. It is incombustible, strong and durable, as well as having the advantage of being self-cleaning. In contrast to previous membrane materials, PTFE coated glass fiber fabric is not designed to fold or to detach from its support.

A critical advancement in the development of membrane structures has been a material known as PTFE coated glass fiber fabric which is very similar to stainless steel in terms of its durability. Its development as a material increased the potential of membrane structures to be applied in a many more circumstances.
However, when this material was first introduced and used in the construction of permanent buildings in the 1970s, there were doubts in some quarters regarding the enduring features of the material. In fact some believed that over time the material would begin to crumble. However, as of yet there is no sign as of fragmentation in any of the buildings in which it was used. However, PTFE coated glass fiber fabric is not always favored. Despite problems with its durability and the tendency for the material to become easily dirty, there is a high demand for PVC coated fabric of synthetic fibers as a membrane material due to its cheap rate of production and the fact that it can be folded (Mewes, 1993).

Membrane structure design techniques are established on allowable unit stress where the figure of 4.0 as a frequency is internally accepted as the safety factor for a membrane material (Clough, 1995). Although this figure is not as safe as it could be, it is considered adequate as it takes into consideration the potential decline in the strength of the membrane material. This safety factor is very low and is possibly only accepted due to the economical costs associated with this material. In the past damage has occurred due to tearing in the membrane material. Such tears begun in small specific areas of the material. In order to ensure adequate safety, the design of the membranes must consider every detail (Berge, 2001).

2.5. Cases of past accidents in membrane structures

There was an accident in a stadium with a retractable roof which was caused by strong winds. These winds fractured the membrane surface as well as causing large tears within the surface. There are 2 possible reasons for this damage. The first possibility is that the membrane had not been cut specifically enough for its design and the second possibility is that the potential pressure of the wind on the surface had been underestimated. An accident also occurred after continual heavy
rain because the wrong type of membrane panels had been used. An air dome suffered severe damage during strong winds. It lost inflation pressure when strong winds caused the membrane surface to shake significantly and make contact with the hard body, following this, many panels were damaged. Another air dome suffered extensive damage as snow built up in the top of the roof causing it lose inflation pressure. Accidents most often occur in air domes where the inflation pressure cannot be sustained. In order to function appropriately it is vital the correct pressure is maintained and therefore in order to ensure safety within these structures it is necessary to control the pressure and organize close supervision of the structure (Cousins, 2002).

A lot is still unknown about membrane structures as they have not yet been subject to a wide variety of accidents from which we can learn from (Kibert, 2001). Therefore, in order to ensure safety within these structures it is necessary to do through risk assessments and attempt to consider all possibilities when designing. However, past accidents involving membrane structures have been due to poor safety standards of materials, not accurately predicting the weight that the roof could hold, using the wrong materials and careless attachment of the membrane structure. If membrane structures are to be universally accepted throughout our society then they must be seen to be as safe as the more traditional structures (Schek, 1974).

2.6. Future Developments

Advancements in the technology of membrane structures are continually occurring, although there are still some problems which need to be addressed. It is hoped that methods will be developed to make membranes structures more permanent architecturally. There is no doubt that as technology increases the quality of the materials used will also increase. In order to improve safety and make it easier for renovation works too take place, it is important that techniques
are procured which allow the membrane material to be regularly replaced independently.

In modern times society is demanding more and more functional buildings. If membrane structures are to meet their full potential then they need to be able to provide high strength, durability, be tear resistant, and be elastic as well as providing both heat and sound insulation.

2.6.1. New Capacity – Translucency

One of the advantages of certain membrane materials is the transparency and the ability to shape light within a structure. As such the architects using membrane structures are often thinking about how they can design and shape the light. Glass incorporated into the membrane structure is able to partially control heat and light within the interior of the building (HeeKyun, 2005).

As its deficiencies in terms of strength and fireproofing qualities render the use of film problematic, as a building material it has significant potential. Currently, highly transparent membrane materials are being developed and if a sufficient level of performance is achieved it will greatly change the fate of membrane-structure buildings (HeeKyun, 2005). However, several significant questions have been identified that remain unanswered. For example, when transparent membrane materials are used to construct closed spaces what kind of heat load is produced? What mechanical systems or construction methods need to be created in order to efficiently address this heat load? What is the appropriate response to heat radiation in more open spaces? Nonetheless, the development of transparent roof membranes remains appealing because they afford great flexibility insofar as that they can be easily manipulated to fit curved spaces. Furthermore, unlike glass for example, they required minimal secondary members. However, the future development of transparent membrane materials
depends upon the resolution of the issues outlined above.

2.6.2. Surface soiling of membrane materials

Soiling is a pressing problem facing the development of transparent membrane materials as a viable construction material for permanent structures. One of the disadvantages of membrane materials is that they cannot be cleaned as easily as glass. Therefore, soiling of any kind, including soiling from rising resin, vastly reduces the splendor of membrane structures. Several solutions have been proposed in response to this issue. For example, a fluorine-based film to be spread over the surface of the membrane has been developed as a potential barrier to soiling. However, this remains ineffective. Similarly, PVC coating have proven to negatively influence the appearance of the membrane structures. Therefore, it is imperative that a viable solution to surface soiling of membrane materials be developed.

2.6.3. Composite Structures

The lightness and durability of membrane materials is increasingly acknowledged internationally and consequently they are being deployed in a variety of settings and in a variety of ways. For example, they are now commonly used to frame large spaces. In order to create even greater spaces and to exploit the inherent endurance and lightness of the material, transparent membranes are frequently combined with other structures. If the merits of transparent membrane materials are to be fully developed, such combinations are paramount.

Cable structures may prove to be a particularly appropriate match for transparent membrane materials. As mentioned above, membranes are extremely flexible, thus they can support the deformed characteristics associated with cable structures. However, far from being a mere appendage to cable structures,
membrane materials used in combination with cable structures will strengthen the overall finished product.

It is important to note that the use of membrane materials does not preclude the use of other materials. Rather, the advantage and merits of membrane materials are best utilized in conjunction with other structures (Baker, 2000).

The benefits of membrane materials in the construction of buildings have only lately been accepted by society. All those directly involved in construction and design should ensure that the unique characteristics of membrane materials are fully developed so their full potential benefits may be exploited for the good of society. International cooperation and the full exchange of information will be needed in order to undertake this endeavor (Fernandez, 2006).
Chapter 3: Methodology

3.1. Data type

Secondary data was the main type of data used in this study. A variety of different secondary sources were used to provide information regarding the topic. Examples from academic journals and publications were extracted and studied, in order to examine their relevance to the topic. If they were deemed suitable, they were respectively referenced throughout the study and quoted in the reference section.

3.2. Reasons for choosing this method

Information analyses formed the basis of this piece of research. Consequently, the use of secondary data seemed most appropriate. Due to the nature of the study, primary research would have been too difficult to conduct. Additionally, secondary data is much more reliable and valid, providing empirical strength to the conclusions that are drawn. Furthermore, conducting a reliable piece of primary research is very difficult, especially if the researcher is limited by financial and time restrictions.

3.2.1. Advantages of secondary analysis

Secondary data research has many advantages, largely revolving around its broad scope of applications. Researchers are able to easily reference longitudinal or cross-cultural studies, providing a variety of different approaches to a certain topic. For example, a cross-cultural study that examines results from many different countries examines the possibility that there may be spatial
discrepancies regarding a certain topic. A piece of primary research would be specifically limited to one location, thus not accounting for this possible extraneous factor. Additionally, the data tends to be of a very high standard, as it has been published in a credible journal or source. Also, secondary data research saves time and money, in comparison with highly intensive primary research. Furthermore, the simplistic method of data collection allows for greater analysis of information. Therefore, researchers can propose more holistic interpretations of data, based on the variety of different opinions.

3.2.2. Limitations

However, secondary data also has many drawbacks. The researcher may find that the empirical information does not relate specifically to their own research paper. It is difficult to find highly relevant pieces of research that provide empirical strength. It would be futile for a researcher to reference a study that does not especially relate to the topic of the paper. Furthermore, the information may be highly complex, depending on the context of the topic or the type of the source. Consequently, researchers may have to spend much time analyzing this information, adding greater costs to the research process.

3.2.3. Why not choosing the alternative methods

It would have been difficult to conduct alternative forms of research, due to the inaccessibility to a reliable sample. Primary research tends to demand large samples, in order to effectively conduct a useful piece of research. Interviews or surveys require a large representative sample, which this research paper lacked. Additionally, it would have been too difficult to isolate a sample with such an advanced level of architectural knowledge.
3.3. Data collection

As previously discussed, literature reviews formed the basis of the data collection process of this methodology. A broad scope of different sources was examined in order to isolate the most useful pieces of research for this study. The researcher actively searched through a variety of different options to find the most suitable research papers.

3.4. Challenges faced

A variety of challenges became apparent during the process of this study. As discussed, the content of this study is highly complex; therefore all of the referenced literature contained a lot of detailed information. Additionally, the data that was used in this study is unfamiliar to the researcher, as it has not been widely used within the course of the degree so far. Finally, the data sources have many different applications; many interpretations could be drawn from the research, depending on the view of the researcher.

3.5. How the challenges were overcome

To overcome the issue of complex literary references, the researcher decided to widen the pool of sources, in an attempt to find more relevant pieces of research. In doing so, the researcher was able to develop a greater understanding of the topic. Additionally, comprehensive comparisons between literary sources showed which pieces of research were more useful, thus resulting in them being used in the study.
3.6. Emphasis on the validity and reliability of the data

Any piece of research needs to maintain a high level of reliability and validity. Reliability is a measure of the ease at which a study can be repeated. As discussed, this study consists mostly of literary analyses of secondary data; these are very easy to repeat as they are widely accessible and relatively easy to study. Validity is a measure of how successfully a piece of research answers its aim; the comprehensive nature of this study, as well as the extensive depth of analyses, means that it is likely to have high validity, as many different extraneous factors have been considered. It is important to consider these factors, as they add much credibility to a piece of research; unreliable or invalid studies are unlikely to be published in an academic journal, thus rendering the research useless.
Chapter 4: Case Study

In 1990, World Cup was held in Italy and the country has built eight stadiums to accommodate the event. This is one out of the eight stadiums for the event. By rearranging the spectators’ seats within the stadium using 310 crescent shaped concrete beams, an oval shaped is eventually formed. It is split into different segments and one such segment consists of 26 ‘large petals’ located in the upper deck. The building does not longer feels so heavy on the eyes as slits were in placed between the petals. This also demonstrates the circulation areas, accommodating all the entries and exits doorways thus it meets the health and safety requirements. Computer simulations were used beforehand in order to maintain the aesthetic side of the stadium.
A special glass coated with PTFE fibre roof, designed by Over Arup & Partners were used in order to protect the spectators of the outdoor weather conditions. There are two levels to this roof, the principal level consists of box shaped beams built from the top. The second level consists of supporting beams for floodlights and truss made using steel and cables. This method of build has ensured tension within the whole structure. Bristol University has assisted in the project by using computer simulation to monitor the wind flow of the stadium. Arup’s computer programs such as Fablon and General Structural Analysis program were used to create the simulation. This was vigorously tested to ensure the wind does not have an unwelcome affect to the spectators.
There are many concrete beams built on the upper seat tiers in order to support the roof. The roof itself is made up of 26 large panels. “Structural Springs” covering an area of 13,250m2 are in placed between the concrete beams which have sealed off the gap between the upper seating tiers. Despite the dynamism of the elevation and the concrete columns, a constant has been calculated in order to able to manufacturer the required steelworks.

The span of these beams is between 14 – 27 metres. Each roof panels consists of steel plate around its edge. Effectively, the concrete framework follows through on the upper tiers.

“U” shaped trusses were used in order to link the beams together. The floodlights within the
stadiums were supported by these trusses which is routed and accessible throughout the whole roof. 3 slender arch ribs further divide the concrete stands and the trusses. In order to made them as thin as possible as well as making them “in-plane” stiff, a fan of tie rods would stem from each end.

Overall, one can see that each roof panel represent a rib cage for the prefabricated membrane panel that can be stretched. All the 4 sides of the membrane were tighten down with 3 “rib cage” by the biaxial pre-stress and each cage is held down by a cable.
4.2. Case Park Dome Kumamoto – Kumamoto, Japan, 1997

The designers wished for a circle with a diameter measuring 125m to cover the central field. They visualized that along the outer circle, facilities would be set up and that these facilities would be covered with an irregular form.

The plan for the domed space was to construct a variety of original and creative structures and then link them together, rather than simply having one large structure to cover the space.

The architects wanted this building to bring together the latest technology and thinking in order to produce a visually
stunning indoor playground that was also capable of using natural energy in order to reduce waste. To represent these ideals, the architects aimed to give this construction the appearance of a cloud floating over the globe.

The roof was created from a circular double-layered air-inflated membrane structure in order to create the image of the floating cloud above the globe. Additionally, to help with this effect a single layered frame membrane construction was used to conceal the unusual outer section.
Although the roof consists of an air-inflated membrane, all indoor spaces were at a regular pressure meaning that all doors and windows were able to be positioned without restriction from the make-up and position of the roof.

In order to sustain the thick concentration and shape of the roof, a frame consisting of a truncated cone was applied into the center point. This truncated cone allow the middle of the roof to contain an opening. This design allows more natural light and ventilation into the structure.
The ceiling is a curved shape which is caused by the opening in the roof. Echoes within the building are decreased as the curvature of the roof spreads the sounds towards the outer structure.

An advanced type of glass with both features of transparency and shielding known as ‘Honeycomb glass’ is used throughout the air-inflated membrane.

The interior space of this structure appears rich and vibrant due to the natural light which spreads and combines from various sources such as the roof, and the large revolving doors. (HeeKyun, 2005)
4.3. Case Millennium Dome – Greenwich, UK, 1999

In 1996 Greenwich peninsula was selected from 57 contesting sites to host the Millennium Experience. This site had not been in use for a substantial amount of years and had previously been in possession of British Gas and used by other British organizations.

The task of designing the Millennium Dome was substantial and needed to take into account the accommodation of the planned facilities that were to be showcased both inside and outside of the Dome. For example, the Dome needed to take into account the external parks, piers and walks along the river Thames that people would want to utilize whilst visiting the Dome.
The structure of the Dome is vast, taking up 80000 square meters with a circumference of one kilometer. The diameter reaches 364m and the highest point of the dome is 50 meters.

Over 70km of high strength cable were used to hold a series of twelve steel masts in place. It is these masts that held the structure of the Dome in place. PTFE coated glass Fiber was used to make up the roof of the Dome.

The Dome was designed with the internal recreational facilities in mind. As such an arena for dramatics and theatre style entertainment was designed in the central part of the Dome.
In June 1997 work on the Millennium site was initiated. Work started with the construction of the foundations, and then moved onto the process of excavating trenches, draining the site and marking out the circumference of Millennium Dome.

The 12 Masts of the Dome were welded from 1600t of steel in August 1997, before being assembled in October 1997.

In 1998 both the cable net and the roof skin were completed. In late 1998 the Patrons of the Dome completed the inside of the Dome and finally in 1999 the outside of the Dome was fully completed.
4.4. Case Don Valley Stadium – Sheffield, UK, 1990

Don Valley Stadium in Sheffield was built with the vision of the architects involved – to construct a facility that will “match anything anywhere” in mind. Don Valley is a purpose built athletics stadium but also hosts a number of sporting events including football and American Football. The primary purpose of its construction was to hold the 1991 world student games. It was hoped that the construction of this 25000 seat stadium located in the heart of the old industrial city would support the regeneration of the area as a whole.

The structure of Don Valley was created in order to benefit the athletes, and enhance the viewing experience of the spectators.
The race track and the field facilities are actually approximately 4 meters below ground level. This combined with the embankment construction surrounding the track allows the viewers to look down on the events taking place. This structure also serves to provide perfect conditionals for shelter which in turn aids the athletes in recovery and potentially allows them to achieve world record performances.

Sheffield is known as steel city due to its industrial past and reliance on this industry. The architects aimed to connect the legacy of the ‘steel city’ with Don Valley's modern structure by using a steel tube for the super structure in combination with a series of membrane roof canopies.
A 26 meter free beam of Don Valley’s roof weights the equivalent of 40kgf/m² in steel and is created by a special array of 12m high masts, back struts and stays.

Owing to their strong resistance to the effects of compression, circular hollow steel sections are used throughout the structure in order to protect the beam from the compression caused by net uplift due to strong winds.

508 dia CHS is the value for the primary beam, back strut as well as all of the mast members. The stay system is 323.9 dia CHS, whilst the front component is 19meters in length. The under uplift is of equal value to a 6 story high unrestrained pillar.

In order to create stability the masts are arranged in pairs to form tubular ladder frames.
In order to counter the strong pull forces created from the lightweight translucent glass fiber membrane which they support the beams are arranged into a comparable arrangement based on that of the masts. The lower section uses steel A-frames which utilize 508 dia CHS struts as well as an ‘I’ section tie, which combine with concrete elements to form the seated terraces public spaces. Throughout the stadium you can see some of the tubular pipes which serve to hold up the upper floors as well as carrying the glazing and related membrane sun shading. Amongst the seats in the terraces tubes can also be seen. 60.3 dia handrails on 88.9 dia posts form the balustrading. There is room within the stadium to increase the number of rows of seats if and when decisions are made to increase the capacity of the viewers. The grandstand also has a number of attractive facilities including fitness, training and physiotherapy rooms, each of which are equipped with a television.

The Hillsborough disaster which led to the deaths of many football fans occurred just 6 months before the scheduled work of the Lower part of the Don Valley stadium was due to take place. This event highlighted the need for sport venues to address health and safety concerns in other sport venues. The interim report detailing issues surrounding the Hillsborough tragedy was written by Lord Justice Taylor and contained information on the design factors that were a factor in the tragedy. As such the designers were able to review this paper and learn from the mistakes at Hillsborough by ensuring that the design of Don Valley took into account such factors.
The Yulara complex is seen as an oasis as it is located 20km from Ayers Rock, Yulara is found in the desert of the Northern Australia. Yulara is a complex that offers a diverse range of facilities from a luxury hotel to a camping site. The complex was cleverly designed in the shape of a snake which seems to slither in between the red sand dunes. The buildings are protected from the desert as they were constructed within the shallow valleys. The Yulara complex is split into two compartments, in which a number of small structures are used to host an aboriginal housing settlement, housing for staff, sport amenities, service infrastructure and a camping site. These small structures are located within the North and East dunes and can only be accessed using auto-mobiles. The other compartment of the complex consists of a large village located along the West of the development and stretches around the sand hills.

Two hotels form the focal points of the village and are located at the very ends of the development which is described as a spine due to its shape. All of the buildings throughout the development are painted in colors associated with the desert – such as rich reds, shades of brown and rosy pinks - which causes these buildings amplify the vibrant colors of the desert and spread them across the entire complex.
Due to the location of this development, it is not only cut off from many sources of power but it is exposed to extreme conditions such as intense heat, sandstorms and hot dry winds. Therefore, the complex had to be designed in order to provide some resistance to these conditions as well as being able to produce some of its own energy. In order to generate energy a network of solar power systems were designed. The sunlight within the complex was filtered by using lightweight fabric translucent fabric, and the interior of buildings such as the hotel and shopping area were cooled by using double layer fabric. (Cox Richardson Architects and Planners).

Located 460 km away from Alice Spring, the Uluru National Park is located in Central Australia. It is a vast structure which covers 132,500ha. This park is an important is of great importance within Australia as it is home to many geographic wonders such as Ayer’s Rock.
With an average rainfall measuring below 250mm, this area of Australia is extremely dry and also suffers from extremes in temperature which can range from over 50 degrees Celsius to -5 degrees Celsius. As such it is essential that all buildings designed for hosting a large number of people take into account the need to provide adequate shade. Along the spine of the complex, a tensioned fabric membrane creates shade for those in public areas such restaurants and hotel entrances, whilst the spaces outside of the complex are sheltered using sails.

An inverted cone on a 7.2m square module is the second form that is used. Sustained from a repetitive system of masts and straight tie downs, these two types are edge cabled. The roof of the hotel was concealed by a basic saddle surface which makes up the third form. The roof utilized arch ribs and perimeter box gutters which were produced from aluminium extrusions into which the membrane edges were placed into. This method meant that edge cables were not necessary as the membranes were tensioned against the gutter beam boundaries. An additional blanket of shading for the roof was provided by adding mounted sail membranes.

The corner tie force for a typical sail canopy is 8.16ft. To keep the vertical supports slender these forces are carried to ground by angled tie-down cables anchored to simple buried concrete foundation blocks.

The Sarna Company provided a PVC coated polyester cloth which contained a unique extra top coating as the material used to make up the membrane.
Aerial view of the central facilities of the hotel.

Site plan.
4.6. Case Yao-Yuan County Arena – Taoyuan, Taiwan, 1993

Located in the outskirts of Taipei, Tao-Yuan County shaped the construction of the Tao-Yuan Country Arena – with a capacity to seat 15000 people - for the purposes of providing sport development and hosting entertainment events within the region. The design for the Tao-Country Arena was influenced by that of the Olympic Gymnastic Arena which is located in the capital of South Korea. It was designed in line with a ‘tensegrity type’ dome using the Geiger Cable Dome system due to the needs for allowing maximum daylight within a circular structure.
The peripheral area of the Dome is likened to that of a brim of hat due to the deep concrete rim around it. This effect is created by the widening of the compression ring with gutter elements. The trenches are dug deep to highlight this feature and draw attention to the ring around the building.

The roof of the cable done utilizes three tension hoops and spread across an area of 12p meters. Due to its ability for long lasting life PTFE coated glass fiber fabric was used to make up the roof membrane.
Conventional cable had to be used for a significant proportion of the main cabling within the roof structure, as the roof structure was designed to be very quickly assembled. This cabling enabled the cable/strut network to be quickly erected. Following on from this, the complete network was elevated and sustained with seven wire pre-stressing tendons which were used for the outer diagonal cables.
4.7. Case San Diego Conventions Centers - San Diego, USA, 1989

The San Diego Conventions Center’s 91.5m clear span roof across both the outdoor exhibitions and the special events area is created by supporting masts – which lay on suspension cables that are 18.3m away from each other - which sustain a tent shaped tensile structure.

The external appearance of the building is created by triangular concrete buttresses which receive their load from the flying masts. There are five corresponding bays each of which has two tent peaks. Between the ridge cables, valeey cables and edge catenaries are extended fabric cables. Suspension cables go through the roof as they link the pier tops with the base of the masts.
The roof of this structure creates an illusion of ‘floating weightlessness’. An ingenious technique of design allows the creation of this effect. A horizontal flying structor with end points shaped like a folk is used in the design in order to allow the two ends of the structure to remain open and independent of any supports by balancing the horizontal tensile forces from the stressed fabric. It is the combination of these flying masts and large openings which allows the roof to display such an original effect.

Present in the center of each bay are small oval openings which exist in order to provide ventilation to the building. These openings are cleverly shielded from the rain by another fabric cover floating which lays above the primary tensile structure. The rain cover has a vibrancy about it, and it combines with the
main roof and the building as a whole to project a visually stunning image that has catapulted this building as one of the main structural attractions of San Diego. As such it has become one of the most important and famous of the numerous tensile structures.

In order to conserve the effect of floating lightness, plans were being made to renovate the area into an indoor enclosure which would consist of a glass wall of 91.5m supported by a cable.
Perspective of the membrane roof and cables by computer.

Section; scale: 1/2,000.

Second floor plan; scale: 1/3,000.

In Paris, the structure known as the ‘Grande Arche’ consists of a hollow cubes with sides measuring 100 meters in length. This building was designed by J.O.Spreckelsen from Copenhagen who was the winner of an international competition in 1983. A huge canopy known as the cloud, or the Nuage due to Spreckelsens vision of floating mist above the ground was erected within the Arche in order to protect the structure from the elements. The canopy occupies a surface area of 2300 square meters and its span reaches 70 meters.
Spreckelsen also produced extensive blue prints for his vision of smaller clouds ascending over the Paris surrounding the Arche. It is a shame from an architectural perspective that these plans were never carried out on the structure. 

There were numerous problems which needed to be resolved concerning the design of the structure. Firstly, the size and scale of the elements that were to make up the Nuage were of vital significance and had to be considered carefully. Secondly, architecturally creating the features of a cloud such as the thickness, density, and random shape would be a difficult challenge.
In order to achieve this, a free standing tower lift would penetrate the Nuage and make up a significant portion of an arc of canopies ascending above the Paris.

The hollow cube was designed to bombard the surface of the canopies with specific wind pressures that were first tested through wind-tunnel simulations at the CSTB in Nantes.

In addition to subjecting the structure to environmental simulations to test the effects of the elements such as wind snow, temperature, and support movement the structure was also designed with fire safety in mind.
In fact 16 separate fire situations were analyzed in order to design the structure to reduce the identified risks in the studies. With the results of the fire scenarios in mind, each of the individual buildings are segmented horizontally at the seventh level to reduce the effects of fire. Additionally a fire escape path exists in amongst the individual building. In the event of a fire occurring in any of the buildings the suspended Nuage is able to disconnect the support cables within any the segmented areas.

A combination of 20mm – 80 mm spiral strand construction and locked – coil cables were used. In addition
to specifically made steel castings needed for this unique structure, the Contractor specifically produced the end fittings of the cables as well as the nodes on order to enable ease of rotation.
4.9. Case Good Shepherd Lutheran Church – Fresno, USA, 1982

Structural fabric was used for this church in what is theorized to be the first time that structural fabric was applied to a church. At the time structural fabric was seen as new method and therefore the congregation of the church debated long and hard about whether to allow the use of such technology to their traditional place of worship.

However, the structural fabric complemented the values associated with the church and religion very well. The use of structural fabric allows natural light to pass through in great volumes to fill the structure.
At the very heart of Christianity is the belief in the Trinity (the Father, the Son and the Holy Ghost). In this structure the Trinity is symbolized by three solid and stable wood beams. Fabric connected to beam supports is linked to the points of the triangle. The religious symbol of the Christianity, the cross is placed above this triangle. The triangle represents the start of a voyage. It is elevated through the supporting beams and it has the appearance that each side ascends to one single point. This has connotations that suggest that there is something beyond this life. Three steel cables linked to stacks of concrete rooted within the soil provide tension from the very top. In order to shelter the building from the weather a fabric covering is extended among these forces.
In this building sustained by architectural forces, it is appropriate that people congregate in this church due to their own personal forces. Just as the triangle, is supported by steady beams, the people support each other and find support in their faith which is considered as unshakable.

Although traditional materials are necessary for the construction of other churches, the fabric suited this church very well due to the natural shape of the construction. In fact is was actually cheaper to build with this fabric than it would have been if traditional materials were used. In addition this fabric is able to keep in the heat longer than traditional materials and therefore it is also useful in helping the congregation to save on energy costs.
4.10. CASE Hyogo Prefectural Tajima Dome – Hyogo, Japan, 1998

Located in the Kansai region, the district of Tajima is home to Mt. Kannabe. Mt. Kannabe is very popular and well visited by the younger generation due to its sport and recreational attractions. Universities provide sport training camps in the summer and Ski-ing activities in the winter. The abundance of cheap temporary accommodation in the district means that many young people can afford to visit the district and take part in the sport and leisure recreation opportunities available.

Within the District, Tajima Dome is the focal point of the sport and recreational facilities. This building acts a dome, but also houses an information centre with an attached bridge.
The building has a large Dome which can retract giving access to the soil. The building was designed like this so that the soil could be exposed to the natural elements and natural light which is needed to keep it healthy. The Dome stands at 60 meters high and roughly 25% of the Dome can be opened.

The spectator deck within the Dome allows magnificent views of the natural beauty of the mountains within Tajima. Although the majority travel to Tajima for the sport and leisure facilities, the spectacular views of the Mountain range are able to provide many visual delights at the same time. The Dome is an impressive structure in which the north and south sides have a different appearance and function. The south side made of PTFE coated glass fiber fabric is retractable.
Where as a raised roof which consists of metallic members makes up the north side. The north side visually looks like that of a large mountain lodge, a very different appearance to that of the south side.

Internally this Dome seeks to attract a diverse range of people by providing facilities consistent with that of sport museums. Individuals that come into the Dome are able to use facilities that allow them to ‘experience and discover’ in the plaza at the front of the dome. Restaurants can be found at the centre of the building.
4.11. Case Columbus’92 “Bigo” – Genoa, Italy, 1992

1992 marked the 500th Anniversary of Columbus’s discovery of the Americas. To commemorate this discovery area of Genova underwent expansive redevelopment. The old Harbour and the historical city area were combined through this redevelopment. Additionally old buildings that date back to the 16th century were renovated and facilities were newly built such as an Aquarium and the Bigo.

Following the celebration the facilities were converted into a waterfront park which has been managed by the local authority of the city ever since.
Stimulation for the idea of the Bigo came from an oil rig on a cargo ship. Eight masts form the Bigo and it is held up as an Emblem of exhibition. In addition it serves a functional purpose as its elevated position allows people to experience magnificent views of the harbor, the city and the surrounding areas of the exhibition.

The exhibition Plaza was held in “Embrico Wharf” which had a PTFE membrane tent roof formed of glass suspended by cables from four tubular arches,

The exhibition Plaza has been used to host football games and outdoor concerts in the summer and ice skating in the winter since the exhibition came to a conclusion.
Close to the tent are nine kinetic wind monuments formed by Susumu Shungu known as “The Winds of Columbus”. These graceful statuettes get their name because they react to the wind and even transform in different lights. It the material – a laminated PTFE fabric known as ‘tenara’ - that forms them which allows them to do this. They represent the wind that aided the journey that Columbus undertook to the Americas all them years ago. (Shunji Ishida, Renzo Piano Building Workshop).

The Bigo supports a membrane canopy which is 60 meters in length by 40 meters in width. This membrane cover a large proportion of the old harbor which has since been converted into an open square and performance site.
Two sets of ‘cigar-shaped’ developments arising from a small isle within the water on harbor make up the Bigo. The membrane roof is sustained by one of these sets which measures 48 meters long whilst a vertical cable car passenger lift is held up by the other set, the longest boom of which measures 70 meters long. Tie bars with deep foundations below the harbor water are used to hold down both of the sets.

The cigar shape of the booms was created by a special welding technique. The end points of the booms from which the canopy is supported contain segments of 16 cables which serve to sustain slim curved ribs from which the membrane canopy is actually fixed into position.
Made up of PTFE coated glass fiber 5 membrane panels with cabled boundaries form the make up of the canopy. A high quality architectural façade is created the attachment of the membrane to the boundary cable which utilizes a uniquely designed aluminium extrusion and cable clamps.

The gaps between the membranes filled with glass which is maintained from spinetubes which bridge across all of the membrane suspension points.

Under stress of changing weights, the position of the glass in the membrane roof is able to adjust automatically due to a pantograph mechanism.

An analysis of wind data within the area as well as wind tunnel tests were used to predict whether the structure of such an unusual roof would be able to withstand the winds that it would be prone to due to its position within the harbor.

Shingu’s graceful sculptures are found close by to the roof. They are able to react to wind and light due their structural formation and material. “These use flat triangular panels of woven PTFE cloth held within frameworks are that are free to spin simultaneously about horizontal and vertical axes” (Kaltenbach, 2004).
4.12. CASE Campus Center, University of La Verne – La Verne, USA, 1973

The university has come under pressure to improve facilities needed for a diverse and wide-ranging curriculum. For example, the university needs facilities to cater for the arts and improvements in its sport facilities such as a gym. However, issues with funding and budget constraints have made it essential that any adaptations to the facilities must be made economically. A traditional layout was proposed for the building of these new structures, but the membrane structure needed to be changed due to the amount that such a design would have cost.

At the time of building the concept of a membrane structure was a new and innovative idea and expert knowledge of these new structures was not easy to access.
As such many problems occurred with the design, but despite this, the decision to design a membrane structure in conjunction with the university was taken. Within this structure, a first floor training area was constructed as well as a second floor gym. Although all the rooms are separated from each other the doors are not closed off from each other.

Four cone shaped structures form together to make up the roof, with four masts accompany the four cone shaped structures tilted at a 15 degree angle. Attached to both the masts and the concrete foundation ring on the outer sections are the support cables.

Where the cones cross over, valley cables are strategically places. A recently invented PTFE coated glass fiber fabric makes up the membrane surface that covers this structure. As the inside of the drama lab had to be darkened, the drama lab was set up in another building, although architecturally it was designed with a similar form to keep in tune with the structure as a whole. From the high point of the mast exists cables which link to a boundary ring beam and the membrane surface administers the bracing.
Due to the relatively low cost of construction, membrane structures were often the first choice in the past. In the early years people associated membrane structures with tents, and it was only thanks to investment and development in membrane structures from the USA that advancements were made in the technology. How to input sprinklers and air condition in conjunction with the new membrane structure was a major challenge for those using this new technology. This challenge was made harder by the face that this was the first project of its kind, where the membrane was designed to be a fixed architectural material as opposed to a structure that was replaceable and foldable, as had been the case with previous projects. (prof. Kazuo Ishii, Yokohama National University)
The plans for the structure had included lighting up the internal structure by allowing natural light to be spread by the membrane. Unfortunately, state law decreed that specific standards of fire-resistance had to be met including providing sufficient insulation from heat. Therefore, it was necessary to connect two inches of combustible heat insulation material to the roof membrane which would in effect prevent natural lighting from passing through.
Chapter 5: Analysis

5.1. Characteristics of Membrane Structures

5.1.1. Larger Span

In 1985 a tennis court with a height of 15m and 45.2m span was built in the International Sports Expo in Japan. In the same year, The Calgary Stadium was built in Canada, which is 36.5m in height, 112m in span and 11150 m² in covered area. In 1988, the Tokyo Dome was built, which is 201m in span and 56.19m in height. The Georgia Stadium built in Atlanta, US has a major axis of 235m, has a minor axis of 186m and is 79.24m in total height. Based on pertinent data, it is speculated that the larger the span of a building, the better the application of membrane structure will embody its economy (Brown, 2001).

5.1.2. Beautiful design with fashion sense

Membrane structures which break through the structural form of traditional building, is easily manipulated into various types of shapes and is rich in color. Therefore they are easily formed into night scenes with the coordination of light. This brings modern beauty to people. What is more, in combination with technological progress, membrane structures are known for use in hi-tech modern buildings; the buildings in 21st century.

5.1.3. Reduce energy-consuming

Membrane material is relatively good in transmission of light. It has a light transmittance of approximately 7% to 20%, thus full use can be made of natural
light. During the daytime, without any artificial lighting provided, it can completely satisfy the needs of various athletic contests. In addition, membrane material with a reflective index of light over 70% can form a soft scattering of light in a room with sunlight in order to make people feel comfortable and dreamlike.

5.1.4. Rapid construction speed

The tailoring of diaphragms, the manufacturing of steel cables, steel structures etc. are finished in factories, and can be used in combination with lower reinforced concrete structures or structural components. Only linkage, installment, positioning and stretch-drawing of steel cables, steel structures and diaphragms are carried out on the construction site, thus the installment of construction on site is relatively easy, quick and convenient.

5.1.5. Apparent economic benefits

Although, presently construction projects with a membrane structure require an initial and once-off high investment, the daily maintenance cost on this type of structure is negligible (hence the label ‘free maintenance structure’). Thus, in the long-term, the economic benefits are quite apparent. If this type of structure is applied to buildings with a super-large span, more obvious advantages in price will be seen. The economic advantages of membrane structure are positively proportional to the spatial span of a building and the technical difficulties associated with construction.

5.1.6. Safety and reliability

Membrane structures are light-weight and its earthquake resistance is
relatively good. Soft membrane structures can tolerate a huge amount of displacement and overall collapse of building is uncommon. In addition, membrane material is generally a flame-retardant material. The fire hazard is minimal.

5.1.7. Easily made into a detachable structure, easy to transport, and can be used for touring performances, exhibitions and etc.

For example, a music studio designed and made by a company in America, covers an area of over $300m^2$. However its dismantlement and re-installment only takes six hours.

5.1.8. Broad scope of application

From the perspective of location, membrane structures are from Alaska to Saudi Arabia. The scale of the structures range from small one-man tents and garden pieces to large buildings that cover with thousands even hundreds of thousands squared meters of area. Some have even imaged conceived a small city make of membrane structures.

5.2. Basic Properties of Membrane Material of Building

5.2.1. Composition and Classification of Membrane Material

The development of membrane structures is closely related to research on and the application of membrane structure. From early examples such as PVC, PTFE to the later ones such as ETFE membrane material, the development and application of each new type of membrane material has sharply impacted upon
the development of membrane structures. Contemporaneously, the application of construction membrane comprises two categories of membrane; a coating fabric and a thermoplastic compound.

### 5.2.2. Coating Fabric Membrane

Coating fabric membrane material is a type of composite material and is generally composed of a substrate, coating and surface course, shown in Fig. 5.1. A substrate is weaved through various textile fibers which determine the properties and structural mechanics of the membrane. Coating and surface course can protect the substrate, and are designed to be self-cleaning, protect against pollution, and durable. Examples of Common coating fabric membrane materials include glass fiber membrane materials made from Teflon coating (generally called PTFE membrane material) and glass fiber membrane material made from PVC coating (generally called PVC membrane material).

![Fig. 5.1 Compositions of Coating Fabric Membrane Material](image)

PVC membrane material is cheap and is divided into several colors such as white, red, blue and green. It is applied broadly. Soft membrane material with
good tensility is easy to make and to stretch, thus it is easily adaptable to tailoring errors. However, its durability and self-cleaning properties are poor. Its properties will change due to outward movement of the coating mold-increasing agent and ultraviolet effects so that its surface gradually turns yellow and sticky over time. Moreover, dust and dirt in air are attached to membrane surfaces and stain the surface and thus reducing light transmittance. Thus, its service life is decreased. In order to improve the durability and self-cleaning of this type of membrane material, a PVF or PVDF surface course can be added to the surface of coating.

PTFE membrane material has good durability and does not turn yellow or moldy in the atmospheric environment. Additionally, rainwater will flow away after forming water drips on the surface as it has good self-cleaning properties. However, PTFE membrane material is more expensive and is stiffer. Thus, the folding & rolling of material during transportation and construction can lower its strength, the convenience of construction of the membrane material is poorer, and consequently refined calculations are required during design and tailoring processes.

Substrates of membrane material are weaved into using glass fiber or polyester fiber yarn. Glass fiber has a certain flexible capacity and a higher elastic modulus and strength than polyester fiber, however it gradually becomes smaller. Therefore it does not age well nor does it have a long service life. However, due to its brittleness, glass fiber should be processed precisely, treated properly and carefully. It should be borne in mind that humid and hot environments an impact on its mechanical property. Polyester fiber, on the other hand, has a longer life, deformation and it is easy to install. However, long-term tension and ultraviolet light will gradually result in ruffles on the membrane surface. Perception and light transmittance are both affected over time.
Basic methods of weaving yarn into substrates of membrane material are plain weave or panama weaves. Plain weave, also called as basket weave, is a process that warps yarn tightly to be straight line while weft yarn crosses upper and lower parts to bypass warp. Warp yarn is weaved orthogonally at a right angle to weft yarn, shown in Fig. 5.2(a). Plain Weave has several variations of method. For example, weft yarn can bypass a warp yarn from below, then three warp yarns from top. When the knitting tightness is relatively high, a substrate of plain weave with relatively high tensile strength is easily treated directly by a liquid coating agent. However, more coating materials are needed when the thickness of the substrate equals that of nearly three-layer fiber yarns. In contrast to plain weave, several fiber yarns can be weaved one time, shown in Fig. 5.2(b). As shown in Fig. 5-2 and Fig. 5-3, Panama Weave weaves two or three yarns at one time in the warp direction and the weft direction. When the same fiber material yarns are adopted, membrane material made using the Panama Weave can weave several yarns one time. Furthermore, its mechanical properties are better than that weaved by single yarn in plain weave.

![Fig. 5.2 Weaving Methods of Yarns in the Substrate of Fabric Membrane Materials](image)

Common resin coating materials include PVC and PTFE. The earliest application used was PVC which has relatively good flexibility and is easy to process. However, it reacts poorly to ultraviolet light, thus chemical changes are common following long-term exposure to sun. Furthermore, it is a poor self-cleaning material. Therefore, membrane materials externally coated with
PVC are generally applied in temporary structures. However, PTFE is an inert material and thus does no react to exposure to ultraviolet light. Furthermore, PTFE has a long life in terms of light transmission and self-cleaning, fire-retardation. In addition, it is not flammable and its opaque color (initially cream-colored) endures over a long period (25-30 years). Thus, it is commonly applied in permanent constructions.

5.2.3. Thermal Polymerization Compounds Membrane Materials

Thermal Polymerization Compounds mainly refer to ethane-ETFE, and are often applied in buildings with high light transmittance and rich models. In comparison to coating fabric membrane materials, ETFE membrane materials are lighter and thinner, and light transmittance reaches up to 95%, and thickness is often smaller than 0.3 mm (Kaltenbach, 2004). Although the strength of ETFE membrane material itself is high, its thickness leads to common applications of the material in inflatable membrane structures. These are structural entireties composed of several two-layer or three-layer air mattress units with a span of usually not more than 5 m.

5.2.4. Physical properties in building of building membrane properties

As a type of structural form with intensely artistic expressions, the higher degree of physical building properties of membrane materials should also satisfy the needs of the membrane. Physical building properties include several aspects such as weather resistance, optical property, acoustic property, thermal
property, and fire-resistance property. During the design of membrane structures, the physical architectural properties of each type of membrane material, in combination with the overall properties of membrane structure should be fully understood. Proper materials should be chosen to correspond to the designs in order to obtain optimal architectural, economic and technical effects.

5.2.5. Weather resistance of membrane materials

Membrane material, as the covering system of building, is often directly exposed to the external atmospheric environment. Thus it is affected by natural phenomena such as daylight, temperature variation, rain wash and dust erosion. Thus, the appearance and color, brightness and strength of the material all gradually deteriorate over time. The weather resistance of membrane material is a comprehensive index that outlines its years of service, its aging resistance, self-cleaning ability and intensity attenuation.

Coating materials such as PTFE and PVDF on the surface of membrane material stem this process. Both are inert materials, thus their chemical properties relating ultraviolet protection, aging resistance and corrosion resistance are better than those of PVC coatings. In general, the service year of a PVC membrane material with coated PVDF surface course is over 25 years while the service year of PVC membrane material with coated PVDF surface course is 10 to 15 years. Therefore, membrane material can be broadly used in permanent buildings (Kaltenbach, 2004).

At present, weather aging experiments are often undertaken to evaluate the weather resistance of a membrane material. Generally speaking, tests investigating the effect of natural climate aging and of artificial weathering aging are conducted. Laboratory tests often adopt artificially accelerated climate
aging experiments, referred to as Xenon lamp aging experiment. The light source of the xenon-arc lamp is adopted to continuously illuminate the membrane while temperature, humidity, radiant energy, rainfall cycle and time are controlled to imitate and strengthen principal environmental factors such as light, heat, oxygen, moisture and rainfall. In natural climate conditions the speed of aging of a sample and the differences of a sample's tensile strength under radiant energy over the course of time is regarded as an indicator of weather resistance.

5.2.6. Optical property of membrane material

The optical properties of membrane material refer to of the effects of membrane material on light of various different wave bands, including such properties as reflection, transmission, absorption and scattering. Different membrane materials display large differences in reflection, absorption and transmission of light in each wave band. In general, membrane material has relatively good light transmission. Light transmittance of natural light of fabric membrane material can reach 20%. However, in double-membrane buildings, built in accordance with relatively high thermal heat-insulation properties, light transmittance reaches 4% to 8%. However, the light transmittance of ETFE can reach 95%, which exceeds that of clear glass(Kaltenbach, 2004).

Inside membrane structure buildings transmission light produces uniformly diffused light. The light has no shadow, no dazzle and no significant direction, thus it is gentle and uniform. During daylight hours, it will satisfy the light requirements of various indoor activities. Therefore, membrane structures are especially applied to buildings that demand higher lighting specifications, such as sports facilities, exhibition halls and patios. In addition, during the night, the surface of buildings with membrane structures can give off a soft light, which
can be advantageous in terms of advertising and in increasing the ease with which buildings are identified.

When interior lighting is used, lamps should be kept at a proper distance from membrane surface to prevent the heat given off by lamps from searing the membrane surface.

### 5.2.7 Acoustic properties of membrane material

The acoustic properties of membrane material are similar to its optical properties and include reflection (reverberation) and transmission loss properties for the various frequencies of sound waves. Reverberation and sound absorption properties comprehensively determine the quality of audio and the soundproof properties of buildings with membrane structures. Single-layer membrane material has poor acoustic properties and can result in strong echoes and weak sound absorption. In addition its soundproof volume is also lower than that of a general palisade structure.

With respect to the vibration of sound waves, membrane material fabrics have very strong reflectivity which increases the noise level inside buildings with membrane structures. Buildings with inner concave, in particular, such as air supported membrane structures or arch supported membrane structures, the ceiling can collect the reflection of sound waves to further impact upon the indoor acoustic environment. However, this relatively poor sound insulation capacity determines that membrane structures are not applied to building facilities that demand high noise reduction.

In general, corresponding architectural measures need be taken to improve the acoustic environment of buildings with membrane structure. For example, the
addition of a light and poly-porous bottom cloth to the membrane can effectively reduce reflection of sound wave and increase attenuation of transmission of sound waves. Perhaps an acoustic screen which is hung on the ceiling of membrane structure can increase the absorption of sound waves. Changing the curved shape of ceiling so that direction of reflection is changed will also have an impact. Furthermore, specialized sound-absorption membrane lining can apparently lower reverberation to increase sound absorption. This has produced good results in the Georgia Dome and New Denver National Airport where such lining has been applied. However, when choosing these technical solutions, we must fully consider the impact of these methods on the performance of the membrane structure in relation to lighting, and fireproofing, for example.

5.2.8. Thermal properties of membrane materials

The thermal insulation performance of buildings with membrane structures is poor, and at present widely used membrane materials cannot limit the impact of internal environment very well. The heat transfer coefficient of single-layer membrane material is large, and refrigeration-consumption is also high. Therefore, it is only applied to open buildings or in areas with warmer climate. When the thermal insulation property of a building is required to be high, two-layer or multi-layer membrane structure can be adopted. In general, there should be a 25-30cm air buffer between two membranes.

Cold condensed dew inside the membrane surface is also a problem that needs to be considered. When a membrane structure is applied to buildings with larger sources of interior humidity such as swimming pool or a botanical garden for example, damp air easily turns into dew on contact with the internal surface of membrane. Therefore, measures such as indoor ventilation, installation of a cold
condensed water drain or air circulation system should be taken.

5.2.9. Fireproofing performance of membrane material

Membrane has a good fireproofing performance. The substrate of membrane material is itself non-inflammable or flame retardant. Glass fiber is non-combustible material while polyester fiber is non-flammable material. When membrane material is applied in half-open buildings such as the grandstand tent of stadium, the awning of public facilities and architectural art sketches and in temporary structures fireproofing safety need not be taken into consideration. However, when membrane material is applied in a roof system of totally enclosed and permanent buildings, as the fireproofing of a membrane material in terms of fire-proofing, smoke volume, toxicity and structural collapse should be comprehensively considered in order to judge its fire-proofing performance compared to traditional fire-resistant and fire-proofing methods. In enclosed buildings, utilization of PVC membrane material simply cannot be denied.

After a fire is lit, PVC membrane material is burned through in the third minute and twelfth second to form an open hole corresponding to the size of contact surface of flame. Thanks to this hole, heat, smog and gas can be automatically excluded. This open hole remains until the fire is extinguished. Early occurrence of the hole results in the emission of heat & smoke from the building and postpones the collapse of the steel structure, which is beneficial for staff in public places as more time is given to evacuate. In comparison, PTFE membrane material only crazes at the joint of membrane surface in the third minute and 35th second after fire is lit, and finally comes off in chunks along the joint(Kaltenbach, 2004). It is found from test analysis of interior membrane buildings that the volume of CO and CO2 from PTFE membrane material is at
least over double that of PVC membrane material. PTFE membrane material also produces the toxic gas HF at a level that exceeds critical concentration while PVC membrane material when burned through does not show evidence of HF. Therefore, it is concluded that the fire-proofing performance of PTFE judged by membrane material in accordance with certain standards does not conform to the practical reaction of membrane structure under fire hazard; therefore PVC membrane material is better (Kaltenbach, 2004).

Maintaining the stability of the framework of membrane structure in the case of damage of membrane surface is one another noticeable issue connected to the fireproofing of membrane structure. In a membrane structure the membrane material is force-carrying material. Therefore, regardless of whether the membrane material is burnt through or comes off, it is always the first part to be damaged. When the membrane material loses tension because it is damaged, the framework of membrane structure should not collapse.

5.3. Study on the Mechanical Properties at the Joint Node of the Membrane Structure

5.3.1. Basic Principles of Design for the Joint Nodes of Membrane Structure

The development of designs for membrane structure is the process in which the overall design and a detailed design of membrane structure simultaneously interactively influence each other and develop. The basic function of the joint node of a membrane structure is to safely and reliably connect each part of the membrane structure to make a whole. After 50 years of development, the current design of the joint nodes of membrane structure need be beautifully
designed, in addition to their basic functions being realized (Motro, 1996).

5.3.2 Direct and brief force transmission paths can effectively transfer internal force

Negative Gauss Hyperboloid produced by equalization of strain is a necessary condition in which Tensional Membrane Structure keeps stable. Brief design for the joint node can simply and specifically pass on complex membrane surface and force is carried by angle points of the membrane to other parts of the membrane structure so that there is a continuous transmission of force flow in line with the analysis and design model.

5.3.3. Sufficient intensity, stability and durability

Intensity, stability and durability are basic mechanical properties that all building structures must satisfy. With respect to membrane structure, sufficient node mechanical property an important factor that guarantees the overall performance of the structure. In terms of the design of joint nodes, we must consider the possible reduction of the joint node property that may be caused by local stress concentrations and a weakening of the membrane material at the joint point so that the mechanical property of the membrane’s joint point can be evaluated accurately.

5.3.4. Necessary harmony of deformation

In comparison to traditional building structures, membrane structures can produce large deformations under the impact of external loads. In each phase of design of the membrane structure, the large deformation property of the
membrane structure must be considered. With respect to the design of joint points, a certain amount of displacement and rotation must be permitted in order to guarantee accurate positioning. Meanwhile, we must also consider the operability on construction of pre-stretch-drawings of membrane material and twice stretch-drawings.

5.3.5. Integrity of architectural appearance

The strong expressive force that membrane structures offer is one of its principal advantages. Once its mechanical properties are met, the joint point should be as exquisite and small as possible in order to be in line with the overall geometric modeling and architectural appearance of the membrane structure. The impact of joint point on light transmission, gas tightness, water tightness and water draining must also be considered.

5.3.6. Basic forms of membrane structure to link joint point

The specific forms of joint points of membrane structures are complex. Moreover, according to the effects and connection of membrane unit, they can be divided into three basic forms: membrane to membrane, membrane to rigid edge and membrane to soft edge.

5.3.7. Membrane to membrane joint point

The main functions of membrane-membrane joint points are to weave various cutting units of a diaphragm into the whole diaphragm, with necessary diaphragms added to reinforce it. Basic forms of membrane-membrane joint points include heat seals, splints, bonding, sutures, belt and combination mode. Presently, the first three of these forms of membrane-membrane joint points are
most commonly used engineering project.

Common forms of thermal bonding membrane joint points include lapping, single-side back sticking and double-side back sticking, shown in Fig. 5.3. Thermal bonding methods include high frequency heat seals, hot air heat seals and the use of hot soldering irons. Thermal bonding membrane joint points fuse through membrane coating and shear transfer force, and the diaphragm a carries uniform and continuous force, thus its joint strength is strongly related to heat seal form, heat seal method and lap width. For PVC membrane material, considering the solder ability of PVC coating and waterproofing requirements, the most commonly used thermal bonding PVC membrane joint point at present is the single-sided back sticking form shown in Fig. 5.3 (b), where the covering diaphragm is located in the inner side of the membrane structure. For PTFE and ETFE membrane material, overlap joints shown in Fig. 5.3(a) is a relatively commonly used membrane to membrane joint point(Kaltenbach, 2004).

![Diagram of thermal bonding membrane joint points](image-url)
A splint membrane joint point is shown in Fig. 5.4. In the procedure one screws the bolt tight, clamps two rigid splints and two diaphragms in the middle tight, and passes on the internal force of the diaphragm from the bolt-rope of the diaphragm and the rigid splint through friction and extruding force. Determination of the length of the rigid splint depends on the size of curvature of the membrane to membrane connecting line. Splint membrane joint point is often applied in field installations of large membrane units to avoid the inconvenience of processing plants. Moreover, the connection of single-side splint also fits that of the membrane unit and the steel boundary components (Kaltenbach, 2004).

Transfer force connecting splints mainly focus on the extruding force between the bolt-rope and the splint. The clamp force and the individual stiffness of the splint are large enough so that the bolt-rope and the splint of the diaphragm can rely on the transfer force to avoid the phenomenon in which the bolt-rope of diaphragm squeezes into splints. Splint connection does not rely on the screw bolt and the shear of diaphragm to transfer force. Therefore, the open size of the membrane should be 2-3cm larger than the screw bolt so that tearing damage...
from shear stress between the diaphragm and the screw bolt in the open hole can be avoided.

Bonding membrane joint points, whose two pieces of membrane units are bonded together by a special glue water and adhesive, transfers the force through the bonding of the membrane’s coating. This form of joint point is in line with that of the thermal bonding membrane joint point, shown in Fig. 5.5. However, bonding membrane joint point is time-consuming, costly and its quality is not easy to ensure, therefore it is commonly applied in such cases as field repair of the membrane structure and in the installation of twice membrane.

5.3.8 Membrane-rigid boundary joint point

Membrane-rigid boundary joint point is applied in connection with the supporting part between the membrane unit and the membrane structure, such as steel structures, aluminum alloy structures, concrete and timer structures. In essence, the membrane unit directly connects with the metal components
through specialized metal adapting pieces. At present, common membrane-rigid
boundary joint point are pressing plate connections, U-style clip connections
and metal fastening connections. A pressing plate connection is shown in Fig.
5.6. It is almost in line with a pressing plate membrane-membrane joint point in
structure and force-transfer mechanism. The friction from the clamping of the
pressing plate and the extruding force between the bolt-rope and the pressing
plate passes on the internal force of membrane to surrounding components.

(a) Membrane-wood structural rigid          (b) Membrane-steel structural
rigid

joint point                                joint point

Fig. 5.6 Pressing Plate Junctional Membrane-rigid Boundary Joint Point

The u-type clip connection method withdraws the edge of the membrane
through the pressing plate and the bolt-rope first, and then it is connected to the
surrounding components through the U-type clip arranged at proportionate
space, shown in Fig. 5.7. The internal force of the U-type clip fits the
adjustment of membrane boundary and twice the lead-in of membrane stress.
5.3.9. Membrane-flexible boundary joint point

The membrane-flexible boundary joint point mainly refers to various joint points connected to flexible cable unit that includes membrane cover connection, U-type clip, and belt, shown in Fig. 5.8.

The membrane cover connection refers to the cable body that passes through the membrane cover formed by the membrane surface, and its internal force is passed on to the membrane cover from the membrane unit, then on to the cable unit. Meanwhile, joint points are continuous, and the transfer of force is uniform. The membrane cover can be formed by a direct reversal of the membrane material once through the thermal bonding method, and is also formed by the addition of a membrane cover. The joint strength of the membrane cover connection mainly depends on the width of the membrane cover created by a heat seal, which is similar to the thermal bonding membrane-membrane joint point. In comparison, a U-type clip connection fits the condition in which the diameter of a cable body is long and when force-carrying is large, and its connection mode is similar to that of a U-type clip with rigid boundary.
Fig. 5.8 Membrane-flexible boundary joint point
Chapter 6: Conclusions

To conclude, the benefits of membrane structure architectures suggest that they are hugely superior to typical architectural designs. Many features make membrane structures widely appealing to architects. They have many ergonomic benefits, such as their large scale and simple construction requirements. Membrane structures can be easily deconstructed and transported, meaning they have many applications and possible uses. Additionally, they are renowned for being safe and reliable, giving them a high appeal for large scale structures. From an economic perspective, they are very energy-efficient and relatively cheap to construct. Furthermore, they have a positive aesthetic appeal and are considered to be visually appealing.

All of the aforementioned features provide reasoning behind their use in architecture. Furthermore, this understanding allows for a greater breadth of applications. With the development of architectural technology, more designs will start to become integrated into modern day building design. Consequently, architects may find an even more effective design structure to use in future constructions. Essentially, greater research needs to be conducted, especially with regards to new designs, in order to expand our understanding of architectural innovation.
References


