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Analytical Study for the Visual Appearance of Tensile Membrane Structure

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ABSTRACT

In the past, Fri Otto designed Tensile Membrane Structures (TMS) using soap film and large physical models. Nowadays however, complex computational methods are available and can be used to generate an optimal TMS form that can improve the aesthetic aspect of these structures. This research paper presents a comprehensive categorization for TMS gathering all possible present classifications. Besides, the paper discusses the factors that impact and control the design of TMS and identifies the ones that affect the overall visual appearance and perception of TMS structures. The paper also provides a comprehensive analysis of these identified factors to quantify their impact on the final form of the TMS. Three case studies of TMS were analyzed to demonstrate the identified factors and their impact on the TMS. The results revealed that the structure type and material used in TMS are the most affecting factors on the overall image and visual perception of TMS.

Keywords: Tensile Membrane Structure, Visual Appearance, Daylighting,

Introduction:

Unlike conventional building structures, TMS can be distinguished based on their structural concept rather than their building materials. For example, materials such as timber, concrete, and/or steel limit designers to specific structural systems in their designs. While in the case of TMS, there are numerous materials that can be used in the same structural form.

For membranes, the excitement of their exterior sculptural form, beauty of their interior space, purity of their structural system, suitability of the materials used and the apparent comfort of their internal climatic conditions are the fundamentals in securing this aim.[1]

1. Tensile Membrane Structure

Modem construction technologies, such as steel and reinforced concrete frames, seemed to release architects from many constraints of structure. They indeed brought larger freedoms for architects to determine architectural forms. However, such technologies could not free architects an example of a tensile structure is membranes, usually constructed as a set of continuous surfaces, carrying load through membrane action.[2] Form matters associated with scales of construction.[3] Besides, Membrane structures are one form of architectural features 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, they use an Aesthetic and ergonomic feature is becoming more apparent.[4]

A well designed tensile structure is characteristic by structure and materials with authentic expressions.

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There is no part of the lightweight structure that is useless or added on for any reason. Every part of these structures is present by necessity – what you see is the essence of the structure. There are no massive hidden structural fortifications; nothing in the structure has been added for decorative purposes.

These structures are catching people eyes in part because of their obvious contrast to traditional structures. Where conventional structures are sturdy, staid and obviously anchored to the ground, tensile membranes are light, graceful and sometimes give you the impression that they could fly. They are completely different from the tall concrete frames, the steel towers and trusses of everyday buildings. [5]

2. T.M.S Classification

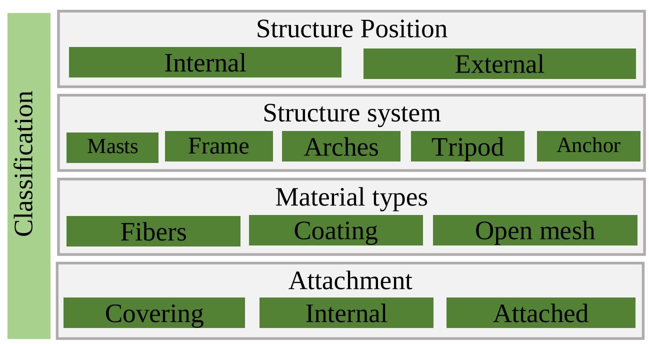

Figure 1: T.M.S Classification
Source: The researchers

In general, T.M.S will be classified according to different aspects as structure, material, attachment relation and application type. In this paper will explain the different structure only because the examples are permanent covering used Fibers as a covering material. See Figure 1.

2.1. Structure Systems Classification

A. Masts Structure

Internal masts: fixed to the ground, the simple and very popular construction method, simple or cone-liked shapes. Regularly used for not much huge span membranes.

Flying masts: known as more advanced solution for large membrane spans.one or more mast is usually attached to a circular or elliptical steel ring. And the entire structure anchored to the main struts, as shown in Figure 2

External masts: the popular ridge and valley form. Main struts are fixed to the ground outside the structure, holding the edge of the membrane at alternating points. Although it has been used to cover large spans "millennium dome-UK".

Internal mast Flying mast External mast

Figure 2: mast types
Source: https://www.wiewioragolczyk.en

B. Portal Frames

Internal Portal Frames: Basic steel frames with horizontal or double pitched skeleton must be used in combination with some other membrane fabrics to achieve the anticlasticity at all ends. Refer to Figure 3.

External Portal Frames: are attached, generally at certain points, to get the regular shape of TMS cones.

Figure 3: internal portal frames
Source: http://www.archixpo.com

C. Arches

Internal arches: Arranged in parallel or crisscrossed line to help the stretching of cables, the arches are capable of being stable themselves. Used for open-plan interiors with large spans.

External Arches: Totally stable by themselves, generating a free large span with no columns space. Fabric is attached at certain points or linearly along the arches structure. Like the internal arches they probably formed in a parallel way or crisscrossed to make sure that the surface had its perfect doubly curved shape. Refer to Figure 4.

D. Tripods

External tripods: For high fixed points, with no need for any obstacles related to stretched cables. The same variations set for masts can be used for tripods.

External Arches Internal arches

Figure 4: Arches types
Source: https://samynandpartners.com

E. Edges with Anchor:

Membranes are attached to the buildings by anchors. Always used in not too large spans. Two types of anchors could be established

- Point anchors: act like external struts or tripods, with the same design consideration.
- Linear anchorages: consisting of shapes anchored to buildings, which should be stable enough and are usually curved to ensure surface anticlasticity. [5]

3. Factors Affecting Tensile Membrane Design

There are different factors affecting Tensile Membrane structure as shown in the next chart, see figure 5.

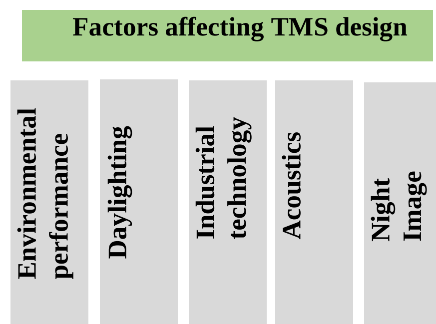

Figure 5: T.M.S factors affecting
Source: The researchers

3.1. Environmental Performance

The environmental performance of spaces enclosed by TMS are still poorly understood, although the structural design of it may be claimed with almost total confidence. Today with the fast technological progress in all fields, we may give a deep concern of how the building envelope could affect the internal environment. On many levels, starting from reducing the amount of energy consumption by using more of daylighting techniques.

This led us to investigate more about the internal environment in TMS buildings and how it plays a useful role in the visual appearance. [1]

3.2. Daylighting

Bright interiors is one of the special features of buildings using membranes as an envelope. It depends on how translucent the membrane material is. It varies from the amount of sunlight penetrating the internal space. Some fabrics reaches 95% of transparency which allows the interiors to be totally lit by the diffused sunlight, avoiding glare problems. This unique characteristic make TMS useful for different functions such as terminals, sport facilities, music and theater activities. [1] See Figure 6.

Figure 6: Day lighting through Sharm el shiekh airport terminal

Source: Hueck Max Egypt – adapted by researchers.

3.3. Industrial Technology

Now days, fabrics used in tensile structure need to high technology process only available in limited number of manufacturers. Due to the light weight and the adjustable form of the fabrics used in TMS, all the manufacturing may not happen at the construction site. Tent are fabricated and shipped long distances to the installation site. However, this is not an effective factor to the cost and it's not an obstacle for the installation, although attention are required when it comes to wrapping, handling, and shipping to keep away any kind of fabric material loss. [6] Refer to Figure 7.

Figure 7: Specifc Technology to install the roof of Sidi gaber terminal

Source: Hueck max Egypt – adapted by researchers.

3.4. Acoustics

Architects can overlook acoustics in designing fabric membrane structure due to a mistaken perception that fabric membrane is acoustically transparent. Acoustics are particularly challenging in fabric membrane architecture due to the physical property of the materials. The acoustical performance of fabrics is reflected highly of sound vibrations, especially in the frequency range from 500 to 2000 Hertz. This means that T.M.S reflects high frequency and mid frequency sounds but, low frequencies pass through the fabric. [7]

3.5. Night Image of Tensile Facades

Technical textile is characterized not only by low surface weight combined with extremely high tensile strength but also by high translucency. Façade's illumination for evening activity is designed in accordance with the degree of translucency. Frequent examples of textile façades carry media messages (eventually advertisement) and interesting aesthetic motives on their areas of stretched materials nowadays. The development of membrane structures, own construction as well as filling materials is constantly in technological development process. So today's possibilities offer to create the tension facade more as an artistic element with the ambition of sculpture. [8]

4. T.M.S Visual Appearance

Unlike any conventional roof systems, Tensile Membrane Structures has a unique visual appearance due to composition between main structure system and the covering material. T.M.S is obviously notable at the exterior scene and extremely exciting for the building users.

Well engineered structures are sensitively detailed to provide visually "clean" connections that are expressive of the transfer of forces between members. Which give the fabric more value to keep all the details clearly seen from the inner or the outer space according to the type of structure used. [7]

Technical textile is characterized not only by low surface weight combined with extremely high tensile strength but also by high translucency. (Up to 95% for ETFE cushions), Façade's illumination for evening activity is designed in accordance with the degree of translucency.

For this paper we will try to investigate the most factors affecting the perception of the T.M.S according to the following methodology, see Figure 8. This investigation will be carried over three case studies in the following section.

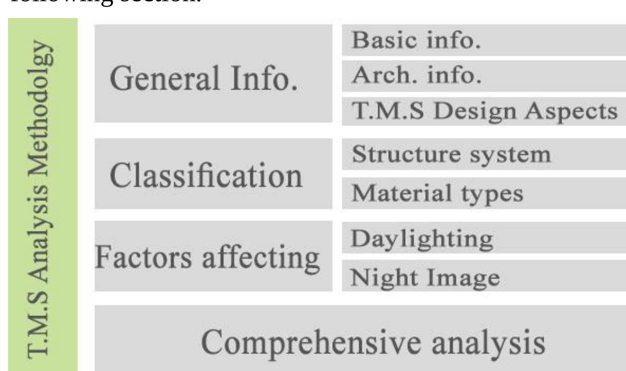

Figure 8: Visual Appearance analysis of T.M.S project methodology.

5. CASE (P1) THE SCHLUMBERGER CAMBRIDGE RESEARCH CENTRE

Figure 9: the Schlumberger Cambridge research Centre.
Source: https://www.hopkins.co.uk

The research building shows the very first big building using glass-fiber membranes coated by Teflon in the UK. Schlumberger building have a contribution in the development of tensile architecture by successfully elucidating the ability of the combination between membrane envelope and usability, rectilinear structure. This project demanded a hub for scientific research into fields of oil exploration, to have a drilling test station, labs, offices and more spaces to be used as workers facilities, see Figure 9. General details are shown in Table 1.

This structure is designed to provide the interaction between scientist, researchers and university personnel. Besides, it provided a clear separation of user's facilities into serving large scale spaces and subdivided spaces. Two one floor sides at both directions are separated by a twenty four meters wide space, enclosed with the single-layer membrane. At the center of the building the space is divided into three sections, two of them are including the drilling test station. The third section is used for a winter garden at which the workers lounge, restaurant and library are sited for better environmental control. [10]

Table 1T.M.S Project 1 general information	
Basic information	
Architect	Hopkins Architects
Contractors	Stromeyer Ingenieurbau GmbH
Location	Cambridge, United Kingdom
Climatic zone	Cold winters and mild summers
Completion	1985
Cost	£7.7 million
function	Research center
Architectural information	
Total area	8,046 m²
Covered surface	2700 m²
Total length	112.5 m
Total width	24 m
Levels	1
Functions	Offices-labs-open garden test station
Shape	Saddle shapes – Ridge and valley
T.M.S Classification Aspects	
Material type	PTFE (Teflon coated glass fiber)
Structure type	External masts – cables
Application	Total Covering
Duration of use	Permanent

Table 1: (Adapted by researchers)

The tensioning of the fabric roof is achieved from the outer with the help of cables in steel. Those cables are been hinged from eight pairs of external steel masts, where the masts are laid on steel lattice frames with the following dimensions: 2.4 m wide and 19.2 m apart. The frames are connected by 1.5m deep and 24m long prismatic steel trusses shaping portals that span the spaces. [11]

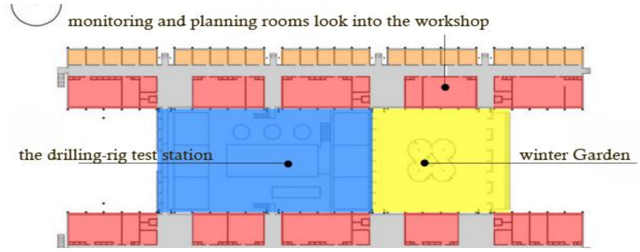

Figure 10: the Schlumberger Cambridge Research center plan.
Source: https://www.hopkins.co.uk
(Adapted by researchers)

5.1. T.M.S CLASSIFICATION ANALYSIS

Material / Material Coating:

Cable / fiberglass / PTFE the fabric covering is Teflon coated glass fiber. It is uninsulated and transmits about 13% daylight, as shown in Figure 11.

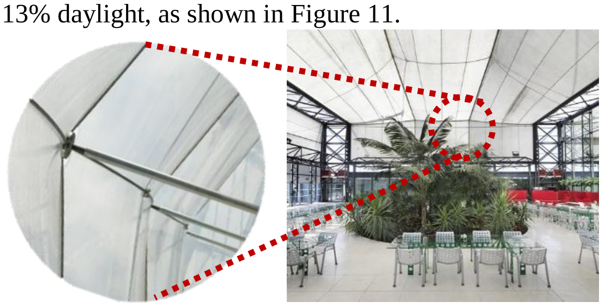

Figure 11: Research Center Coating Material.
Source: https://www.hopkins.co.uk
(Adapted by researchers)

Structure type:

The separation of the fabric roof in order of three main bays corresponds to the 18x24 m structural sections single-layer tensioned fabric panels are clamped at both ends of the research center. The fabric roof is attached to a linear framework, while it is separated from the primary structure by glazing filled panels. Aerial cables, linked to the primary masts by tension rods that would give the external structure its final curved shape. [12], see Figure 12.

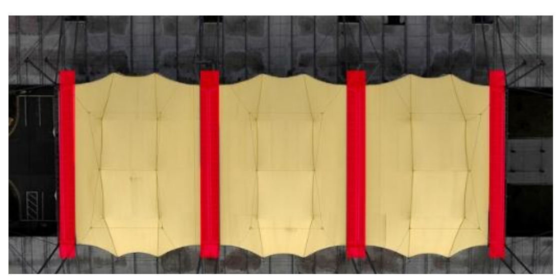

Figure 12: Roof Structure.
Source: https://mapio.net/pic/p-40402541/
(Adapted by researchers)

The prismatic trusses that span the central space which is covered by a single-skin membrane.and separate the membranes are glazed, affording views of the sky and letting a proportion of direct sunlight into the center of the plan. Before that the membrane had been installed and clamped in place, pre-stressed by shortening the links between ridge cables. See Figure 13.

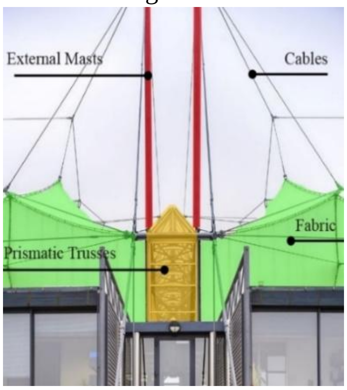

Figure 13: structure composition.
Source: https://www.hopkins.co.uk (Adapted by researchers)

Night image:

Using uplighters fixed to the internal masts structure, these spaces are lit. The fabric surface allows the light to be reflected down onto the internal spaces. [8] (Figure 14)

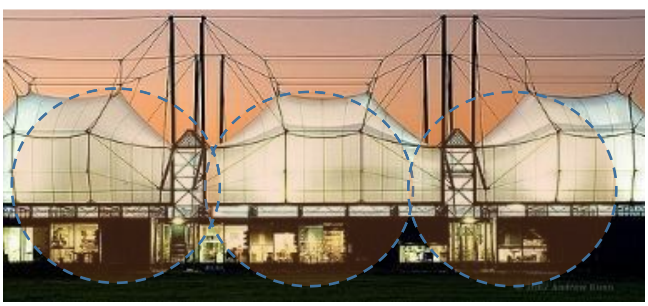

Figure 14: research center night lightig
Source: https://www.hopkins.co.uk (Adapted by researchers)

Natural lighting:

The fabric covering is Teflon coated glass fiber. It is uninsulated and transmits about 13% daylight, see Figure 15.

Figure 15: indoor natural lighting.
Source: https://www.hopkins.co.uk

6. CASE (P2) SHANGHAI WORLD EXPO AXI

Figure 16: Shanghai World Expo Axis..
Source: archdaily.com

Expo Axis is the main entrance of 2010 Shanghai World Expo. It is one of the five permanent Expo buildings; the other four are the China Pavilion, Expo Conference Center, Culture Center, and Theme Pavilion,The Expo Axis consists of the tensioned membrane roof, six single-layer steel-grid shells covered by glass panels, and a three-story underground concrete frame, refer to Figure 16.

Two kinds of computational models are adopted. First one includes only tensioned membrane roof named M1. The second, M2, which includes both the tensioned membrane roof and the steel shells. Table 2 Shows General information about the project.

Table 2 T.M.S Project 2 General information	
Basic information	
Architect	SBA international Stuttgart/Shanghai
Contractors	Shanghai Construction Group
Location	Shanghai, China
Climatic zone	Moderate Climate
Completion	2010
Function	Public spaces
Architectural information	
Total area	280000.0 m2
Covered surface	65,000 m^2
Total length	843 m,
Total width	102.6 m,
Levels	4
Functions	Retails
Shape	Anticlastic
T.M.S Classification Aspects	
Material type	Glass fiber with PTFE coatings
Structure type	External masts – cables
Application	Total Covering
Duration of use	Permanent

Table 2: adapted by researchers.

The Expo Boulevard has a 65,000 m2 membrane roof With a free span of almost 100 m. The roof is carried by 19 inner and 31 outer masts besides six funnel-shaped. the funnel framework shells consisting of steel and glass. Its height is 45 m with a free projection of 80 m. the funnel shape used also to provide direct natural lighting into lower floors, as shown in Figure 17.

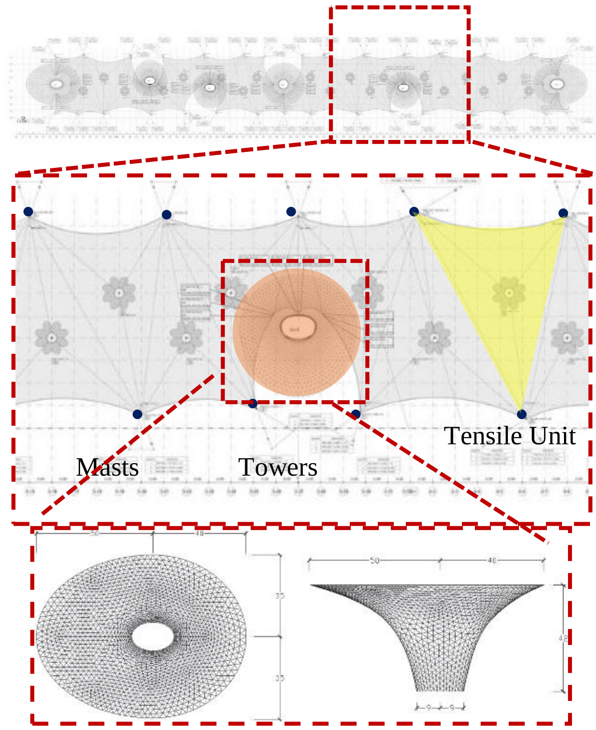

Figure 17: Shanghai World Expo Axis Site Plan.
Source: archdaily.com
(Adapted by researchers).

The supporting points of the membrane roof are supplied by the external towers at two sides, the steel ring at membrane conic bottoms, the steel shells, and the horizontal and inclined cables connected with the internal towers at the conic bottom. The membrane roof itself is strengthened by ridge cables, valley cables, and edge cables, as shown in Figure 18 & Figure 19.

Figure 18: Shanghai World Expo Axis façade.
Source: archdaily.com

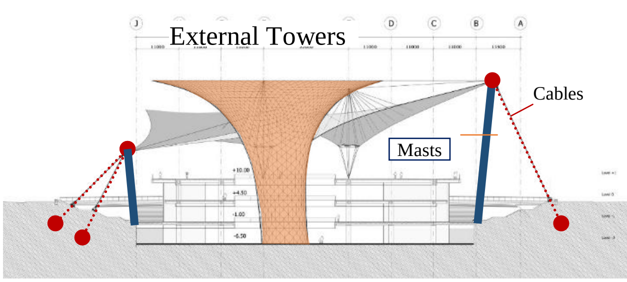

Figure 19: World Expo Axis Section Explain structure Composition.
Source: archdaily.com
(Adapted by researchers)

The supporting points of the membrane roof are supplied by the external towers at two sides, the steel ring at membrane conic bottoms, the steel shells, and the horizontal and inclined cables connected with the internal towers at the conic bottom. The membrane roof itself is strengthened by ridge cables, valley cables, and edge cables as detailed in Figure 20.

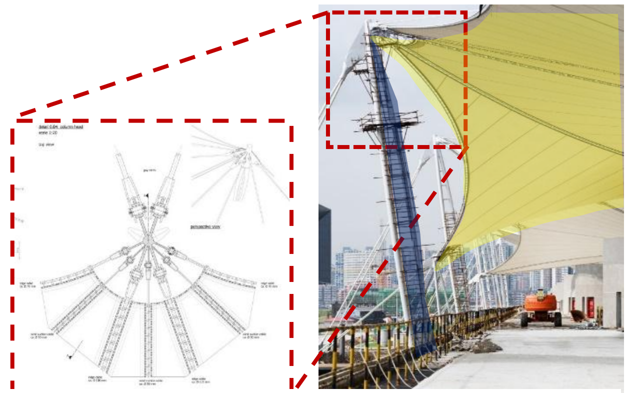

Figure 20: Masts details with fabric and cables.
Source: archdaily.com
(Adapted by researchers).

Structure:

The external towers shaped as shuttle columns consisting of three main chords. Chords are made of steel tubes fixed together by diaphragm plates. External towers can be categorized according to its height. See Figure 21.

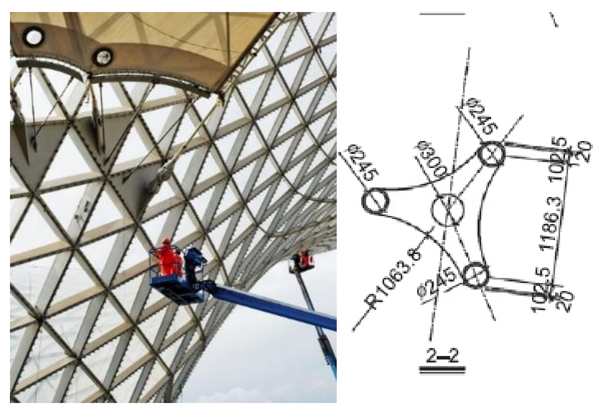

Figure 21: Single layer grid.
Source: archdaily.com (Adapted by researchers).

The shell consist of six single-layer grid made of steel in rectangular section members. The member dimensions are:

- The lengths from 1.5 to 3.5 m.
- The widths from 65 to 120 mm.
- The heights are from 180 to 500 mm.

The axis include two types:

- Larger axis lengths from 16 to 21 m
- The shorter axis lengths are from 12 to 16 m.

Roof Structure:

Roof consist of 69 membrane units each unit can be installed in one step or two units. More than 100.000m2 of PTFE fabrics were used for the tensile membrane structure roof in order to cover Whole Boulevard which summed an innovative and very special spectacular and visual effect. Refer to Figure 22.

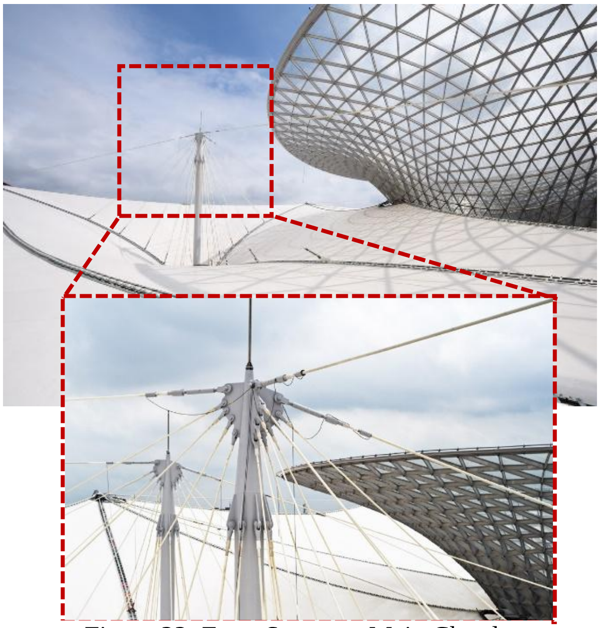

Figure 22: Expo Structure Main Chords.
Source: Source: archdaily.com
(Adapted by researchers).

Factors Affecting Design Process Of T.M.S

Natural Lighting

Internal spaces had its high quality of natural lighting, this because of the mixture between direct and diffused sunlight.it would be hard to achieve such a result using another type of conventional roof. [9] See Figure 23.

Figure 23: Natural lighting at the central spaces.
Source: archdaily.com
(Adapted by researchers).

Night image

At night these spaces are lit by colored uplighters, fixed to the internal Masts at the upper chord steel structure, using the surface of the membrane to reflect light down onto the spaces below. See Figure 24.

Figure 24: Expo diffrent night image.
Source: archdaily.com
(Adapted by researchers).

7. CASE STUDY (P3) KHAN SHATYR ENTERTAINMENT CENTRE

This giant circus is a shopping mall and entertainment centre, looked as tent structure, Designed by Norman Foster. Its quilted fabric roof is controlling the interior temperature to enjoy the artificial beach, with sand imported from the Maldives. A The Khan Shatyr Entertainment Centre is designed to provide the city with a range of civic, cultural and social amenities all sheltered within a climatic envelope - 'a world within' - that offers a comfortable microclimate all year round, whatever the weather. See Figure 25 and Figure 26. Table 3 shows general information about the project.

Figure 25: Khan Shatyr Entertainment Centre Astana, Kazakhstan.
Source:fosterandpartners.com

Table3 T.M.S Project 3 general information	
Basic information	
Architect	Norman foster architects
Client	Sembol Construction
Location	Astana, Kazakhstan
Climatic zone	Cold, snowy climate
Completion	2010
Cost	150
Function	Entertainment center
Architectural information	
Total area	100,000m²
Covered surface	30000 m^2
Total length	200 m
Total width	150 m
Levels	6
Functions	urban- park, 450m meter jogging track shopping and leisure facilities, restaurants, cinemas, entertainment spaces, undulating terraces, a water park, wave pools
Shape	Cone
T.M.S Classification Aspects	
Material type	Ethylene Tetra Fluoro Ethylene
Structure type	150 m mast and cable net
Application	Total Covering
Duration of use	Permanent

Table 3: adapted by researchers.

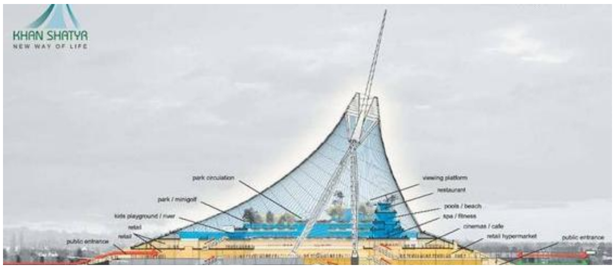

Figure 26: Khan Shatyr Entertainment Centre section.
Source: fosterandpartners.com

Material cladding

the tent covered with a three-layers of ETFE, formed as 3.5 x 30 m-cushions - a very light, economical and thermally efficient solution. The building open areas are tempered, with target temperatures of +14 C in winter and +29 C in summer. Besides, the used cladding is allowing light to flood large spaces and protecting the interiors of the structures from powerful sunlight, wind and snowfall. See Figure 27.

Figure 27: Material Constrcurtion.
Source: fosterandpartners.com

Structure

The mast structure soars 150 meters from a 200 x 195-metre elliptical base to form one of the highest peaks on the Astana skyline. Enclosing an area in excess of 100,000 square Meters.

The tubular-steel tripod structure supports a suspended net of steel radial and circumferential cables.

The project designed a tripod around the central mast to bring the tent to its final standing point. To offer structural stability in face of both the heavy tent load, and there are. The supporting head on which the cables

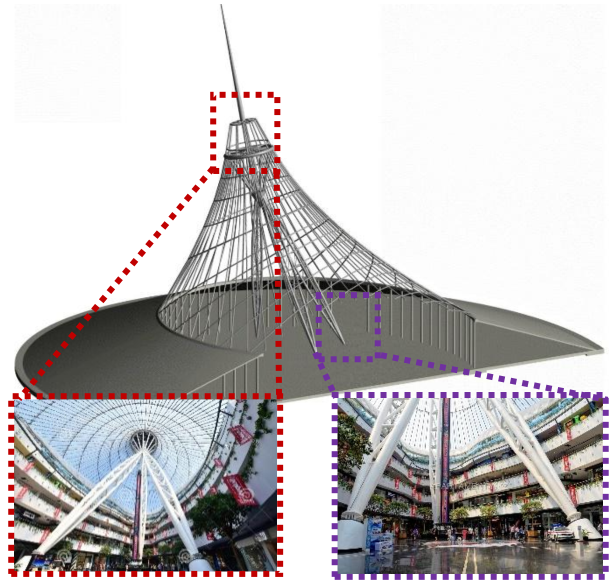

Figure 28: Structure system.
Source: Source: fosterandpartners.com

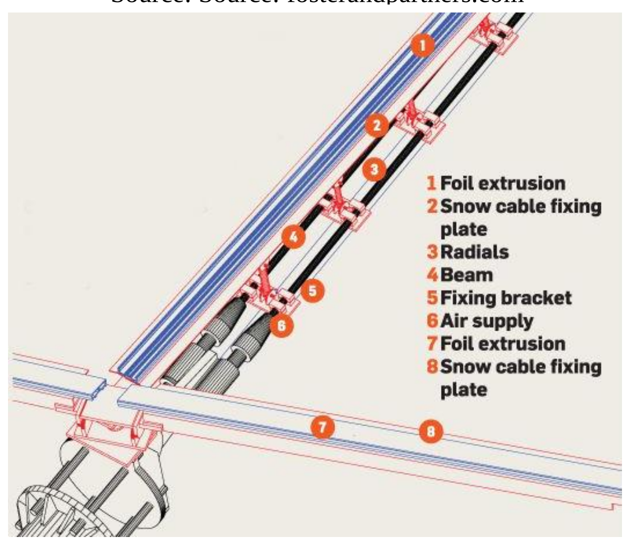

Figure 29: Structure composition.
Source: fosterandpartners.com

were secured, remained the tripod's only movable feature. The tubular steel tripod was welded together onsite and wrapped in temporary covers. See Figure 28 and Figure 29.

Day lighting

The translucent material allows daylight to wash the interiors while sheltering them from weather extremes. Specific enclosures within the envelope are air conditioned, as shown in Figure 30.

Figure 30: natural lighting in inner spaces.
Source: fosterandpartners.com

Night image

The building has a unique lighting system to control the outer appearance of the building in different colors, see Figure 31.

Figure 31: different images at night.
Source: fosterandpartners.com

After analyzing all three case studies in the previous section, a comparative analysis will be held between them. This is to observe the areas of strengths and those of weakness in the case studies, refer to table 4. Thus, this will provide us with the necessary information and conclusions of the analytical part, to determine which factors are the most influencing ones over the visual image and perception of TMS.

Table 4 : Comparative analysis between the three projects				
	According to Classification		**According to Factors Affecting**	
	Structure	**Cladding material**	**Natural lighting**	**Night image**
P1	External masts – cables	Poly Tetra Flour Ethylene - PTFE	Transmits only about 13% daylight but it's clearly enough for the indoor function	Using uplighters by fixing them to the internal masts structure, these spaces are lit. The fabric surface allows the light to be reflected down onto the internal spaces
P2	Internal and External masts – cables	Glass fiber with PTFE coatings	PTFE material allows daylight partially to lit up the interior spaces	Uplighters fixed to the external masts , led lights fixed to the masts
P3	Internal masts and cable net	Triple layer of ETFE formed as 3.5 x 30-metre cushions	The translucent material allows daylight to wash the interiors while sheltering them from weather extremes	The building has a unique lighting system to control the outer appearance of the building in different colors.
Conclusion	Different types of Structure elements highly affects the perception of the entire shape	PTFE Materials are more reliable to use in order to have more attractive visual perception from the outside	ETFE is More translucent than any other materials used helping more natural light to penetrate the indoor space	For the different types of structure elements or cladding material , external light units are needed to be fixed or directed to the skin in order to have a unique visual image for the whole T.M.S

Table 4: Adapted by researchers.

8. Conclusion:

After comparing three of the important T.M.S projects in Europe / Asia with common structure elements and different types of cladding materials the following points were concluded:

- Tensile Membrane Structures have a very different visual image which allows designers, architects or engineers to get a unique experience forming and shaping exciting solutions to regular design challenges.
- Structure elements and cladding material are the dominant factors affecting the whole visual image for the T.M.S projects.
- Steel Masts (Interior-Exterior) are the most interesting Types of Structures we could use to enhance the perception of the visual image as it's clearly seen from inside or far away from outside the building depending on its height
- As for the cladding materials we can conclude that different membrane materials (cushions or fabrics) would give the designer more flexibility to change the visual perception due to the amount of translucency of the skin letting the light through in or out the building.

Recommendations:

- More investigations can be carried out to state more factors affecting the visual perception of the T.M.S
- More analysis should be done in order to study the relation between different factors controlling the visual appearance of T.M.S and social acceptance using more investigations and surveying.

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دراسة تحليلية للصورة البصرية لنظام الإنشاء بالأغشية المشدودة

الملخص:

في بدا ية القرن العشرين ، صمَّم فراي أوتو هياكل معتمدةً على الشد باستخدام فقاعات صابون ونماذج معمارية كبيرة . في الأيام الحالية، ومع التطور التكنولوجي و توافر طرق حسابية معقدة والتي يمكن استخدامها لإنشاء النموذج الهيكلي الأمثل للمبني معتمداً على الأغشية المشدودة وا لتي يمكن أن تُحسِّن الجانب الجمالي لهذه المباني .
تقدم هذه الورقة البحثية تصنيف شامل للمنشآت بالأغشية المشدودة يضُم مختلف التقسيمات المختلفة لهذه المنشآت . ثم يعرض البحث مختلف العوامل المئثرة على تصميم هذه المنشآت مع إستخلاص العوامل المؤثرة على إدراك الصورة البصرية للمنشآت بالأغشية المشدودة وفهم كيف يؤثِّر كلٌ من هذه العوامل على الإدراك البصري و الشكل النهائي لنظام الإنشاء بالأغشية المشدودة. هذا، وقد تم تحليل ثلاث دراسات حالة من نظام الإنشاء بالأغشية المشدودة لدراسة تأثيرهذه العوامل عليها . و لقد أوضحت نتائج التحليل أن النظام الإنشائي المستخدم للغشاء المشدود و نوع المادة المستخدمة به من أهم العوامل المؤثرة على الإدراك البصري لهذه المباني.