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TENSILE STRUCTURES AS THE MOST ADVANCED LIGHTWEIGHT STRUCTURES

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Abstract. *Tensile structures are currently the most advanced lightweight structures. Apart from their very small self-weight, they are also characterized by a double curved form with a negative Gaussian curvature. In addition, this is one of the most recent structural systems to be designed and because of that a lot of research work is still being done on its improvement. This paper will give a brief overview of the development of tensile structures. Their most modern sub-type, membrane structures, was analyzed in more detail. The characteristics of this system, its loading and the structural material it is made of were also studied. Special attention is paid to the form of this structural system. In the end an overview of the most significant objects constructed using the tensile structure system is offered, including the Olympic stadium in Munich as an example of cable net subsystem, and the roof of the central court in Wimbledon and the stadium in Durban as representatives of the membrane subsystem. In addition to the significant advantages of this system, the drawbacks are also highlighted.*

Key words: *tensile structures, membranes, double curved form, prestressed structures, lightweight structures.*

1. TENSILE STRUCTURES

Tensile structures represent the perfect union of art and engineering. They represent spatial structures of a minimalist character. Their form is curved but neat, and the details are either completely eliminated or significantly reduced. These spatial structures are exceptionally lightweight, both in terms of their actual weight and visual manifestation. The shape of a tensile structure obtains another visual level when shadows appear on it, since the play of light and shadows on a curved surface has a dramatic effect. Even though the form of the tensile structure appears to be its greatest advantage in an aesthetic sense, it does not require any forced structural solutions, but is itself the only necessary element

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for the stability of the structure. Thus the form of a tensile structure becomes the most important characteristic both in an architectural and structural sense.

Tensile structures in their most basic form have been in use since early history. Research has indicated that the first tents dated back from approximately 20 000 BC [9]. Quite similar tents are being used to this very day. Their basic function, to protect people from any inclement weather conditions, has remained unchanged, but the improvements in the sense of using other structural materials are obvious. Modern tensile structures usually differ from tents based on their size, degree of complexity, form and structural material, but their purpose is also to protect a great number of people from the sun, rain, wind and snow. In addition to function, tensile structures also inherited their shape from tents, but it had to be modified in order to meet structural requirements. One of the best characteristics of tents is their ability to be put up and taken down very quickly, which enables them to be relocated easily form one place to another. However, modern tensile structures in the greatest number of cases have shed this characteristic, and are not produced as transferrable, even though they are completely prefabricated [14]. Nevertheless, they are still exceptionally lightweight, and as a result offer many advantages in terms of erecting and transport.

Fig. 1 The tent as a model for modern tensile structures

Modern tensile structures were first designed by the Russian engineer Vladimir Shukhov. In 1896 he designed and built two halls with a tensile structural system for the All-Russian Industrial and Art Exhibition in Nizhny Novgorod. However, in the next 50 years no significant objects using the tensile structure were built. It was not until the middle of the 20th century that engineer Otto Frei realized the possibilities that such a structural system had and began developing it. Frei is the most deserving for the promotion of tensile structures; his buildings still stand to this very day as architectural landmarks.

Fig. 2 The first tensile structure (1896) and the German pavilion in Montreal (1967)

Tensile systems can be divided into two sub-systems, cable net and membrane structures [5]. Cable net structures consist of a network of interconnected bearing cables and a cover which can consist of various different, usually transparent materials. The most famous objects built using this subsystem are the German pavilion built for the World Fair Exhibition in Montreal in 1967, and the stadium in Munich built for the Olympic Games in 1972. Membrane structures were designed as a result of the improvement in cable net structures and today have completely replaced them in practice due to their superior characteristics. In the case of membrane structures, there is a structural element which unites a bearing and covering role. This element is referred to as a membrane and the entire subsystem was actually named after it.

Fig. 3 The cable net and membrane structure

Tensile structures differ in many respects from traditional structural systems. Along with pneumatic structures, they have the smallest self-weight, which is several times smaller even compared to concrete shells. The weight of the membrane of tensile structures is approximately 1 kg/m2 [4]. This is achieved by the membrane being only 1 mm thick. Considering the fact that with such a small weight they cannot significantly resist any external load, other forms of stabilization were developed. Due to its small thickness, the tensile structure cannot withstand pressure. That is why tensile structures are stabilized through tensile prestress forces [17]. In order for the structure to remain stable, it always needs to be tensioned in all its points. The material which is used to design membranes possesses special characteristics and will be processed in more detail in the section Materials of tensile structures. Another characteristic of tensile structures is their double curvature. In order for them to be stable, they have to have to be doubly curved with a negative Gaussian curvature. In addition to it being necessary for achieving the stability of the structure, this form significantly contributes to the attractiveness of the tensile structure.

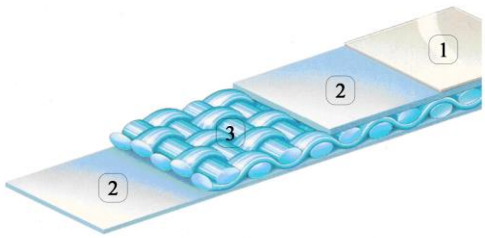
2. Loading and Tensile Structures

Tensile structures are exposed to the effects of both external loading and prestressing. The prestressing that they are exposed to is of significant intensity and is not negligible. The usual value of prestressing is 1 to 6% of the maximum tensile force which the material can withstand. In addition to prestressing, in some cases poststressing is also required. Considering that material under the influence of prestressing elongates, there is a reduction in the prestressing force which requires additional stress. The self-weight of the tensile structure, as we have already mentioned, is exceedingly small, and as such does not have a great influence on the structural calculations. Of all the external forces, snow load plays one of the most important roles. Snow represents a static load which is relatively simple to acquire, based on the defined standards. The inclination of the structural surface can also be taken into account, and it always results in lower loading on the structure. The surface of the structure is usually smooth, so the layers of snow often slide off the object before achieving greater thickness. The wind has a much more complicated effect, in part due to its dynamic nature, and in part due to the curvature of the structure. That is why for the calculation of wind load, we often use scaled models which are tested in wind tunnels or numerical models which are tested using the CFD (computational fluid dynamic) analysis. While snow only acts in a downward direction, wind can act both in a downward and upward direction. Temperature differences and changes are rarely included in the calculation of tensile structures, since due to their small thickness they practically do not represent a barrier to heat transfer. The influence of seismic forces is very small, precisely because of the light weight of the structure itself. The point loads sometimes have an effect on the tensile structure and have to be included in the calculation. They can occur as incident loads, as dead loads or as live loads.

When calculating tensile structures, special attention is paid to the boundaries which the internal forces need to be in under the influence of any kind of external load. Internal forces need to remain tension forces and cannot in any case become compression forces, so their allowed minimum is 0 kN. On the other hand, the upper limit of the intensity of the tension force needs to be taken into consideration. It is determined by the division of the tensile strength with a certain safety factor [12]. This safety factor for tensile structures is greater than for traditional structures due to the unreliability of the production process of the membrane material, the erection of the structure and its connections, and usually has a value of 4 to 7 [6]. An evaluation of the state of the structure is carried out by measuring the intensity of the forces in the structure and the evaluation of the damage to the material. These evaluations should be carried out relatively frequently, at least once a year. In this way, we provide the maximum life span, but also the safety of the structure. In addition to meeting the force level criterion, it is important to meet the requirement of the maximum deformation [11]. Tensile structures are especially susceptible to deformations [19] and that represents one of their biggest shortcomings. Under the influence of external forces, they can significantly alter their form, and because of that we might say that their form is "active". Maximum deformations are not, unlike force, defined by rulebooks, so it is necessary for the engineer and investor to jointly reach a conclusion regarding which value of the deformation is acceptable. It is precisely the deformation, or the change in the form of the tensile structure, that plays an important role in resisting external load.

3. Structural Material for Tensile Structures

In this section we will take a closer look at membrane structures as they are more advanced than cable net structures. Membrane structures are built out of a special textile material, and because of that are sometimes known as textile structures. Two of the most frequently used types of textile membrane material include PVC (polyvinyl chloride) and PTFE (polytetrafluoroethylene) materials [15]. There are also some more modern materials, primarily silicone-based, which have better properties than the aforementioned materials, but are still not widely used, and so will not be discussed in detail here.



1. Top coating
2. Protective layer
3. Textile core

Fig. 4 Membrane material – a textile core covered with protective layers

Even though they are similar to the materials which are used for pneumatic structures, membrane structural materials differ from them in terms of their characteristics. The basic difference between the materials used for membrane structures and those used for pneumatic structures is in the material structure itself. In the case of pneumatic structures, today we mainly use ETFE (ethylene tetrafluoroethylene), which is a material similar to foil and has a homogenous structure in all its points. It is transparent, and very easily connects to itself through a process of welding at higher temperatures. Unlike it, membrane materials have a heterogeneous structure which consists of a textile core and protective coatings, whose joint thickness is approximately 1 mm. The textile core allows material resistance to tension, and represents a load-bearing layer. In the case of PVC material, it is made out of polyester fibers, and the protective layers are PVC-based, while in the case of PTFE material, the core is made of fiberglass fibers, and the protective layers are made of PTFE. The role of the protective layers is to protect the load-bearing layer from the influence of the sun, from the chemicals in the atmosphere, and to ensure the waterproof nature of the membrane. Due to its structure, the membrane materials are not transparent, but they are translucent. The amount of filtered light depends on the type of material. One of the greatest problems of membrane materials is their difficulty to connect due to their extensive number of layers. Any connections are established through welding or high frequency welding. These connections are numerous in every structure, and they must exist in order for us to obtain a double curved form from planar material parts.

PVC and PTFE materials differ from each other, and it is precisely these differences that will determine which of these materials will be used in a specific case. The differences between PVC and PTFE materials are reflected primarily in the greater endurance of the PTFE materials. This includes greater resistance to the forces of tension, and the longer lifespan of the material. PVC materials in practice last between 10 and 30 years, while the PTFE material can be used for over 50 years. The production process of these two materials differs significantly one from the other and it is more complicated for the PTFE material, which is why this material is more expensive. At the same time, it requires special conditions during transport since it is very sensitive to any double-axe folding [10]. That is why in the case of structures with retractable roofs PVC material is usually used.

Table 1 The characteristics of steel and membrane material

	Weight	Tensile strength	Thickness
Steel	7850 kg/m^3	400000 kN/m^2	/
PVC type 2	1 kg/m^2	80 kN/m	1 mm
PTFE type 4	1 kg/m^2	90 kN/m	1 mm

4. The Form of Tensile Structures

4.1. Basic forms

The form of tensile structures must always be doubly curved with a negative Gaussian curvature. Even though this may seem like a great limitation in terms of diversity, there are actually numerous forms which meet the given requirement [16]. In addition, these saddle forms are not often used in architecture, and there is still a high demand for this form. All forms of tensile structures can further be divided into four subcategories: hyperbolic paraboloids, cone forms, wave forms and forms with a supporting arch. However, the most widely used are hyperbolic paraboloids and cone forms. Their basic forms are given in figure 6 [13].

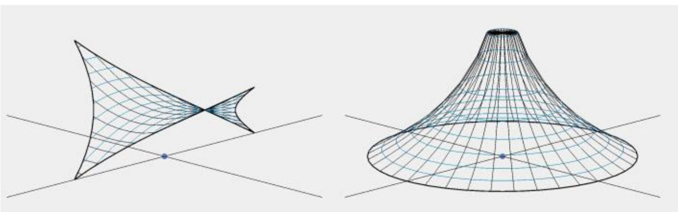


Fig. 5 The hyperbolic paraboloid and cone form

The form of the tensile structure is obtained as a result of a parametric process [2], and depends on prestressing and boundary conditions. Prestressing in the case of tensile structures is always defined through two main directions in the structure. The intensity of prestressing along two main directions is not important for the determination of the form of the structure, but their ratio is. If the intensity in both directions is the same, then the structure will have the form of a minimal surface [18]. The proportional increase or decrease in the intensity in both directions does not have an effect on the change in form. The boundary conditions include geometry and the type of supports used in the structure. The spatial arrangement of the supports has the greatest influence on the final form of the structure. The types of support can be rigid or elastic, where the rigid kind allows smaller deflection under the influence of external load. The form of the tensile structure also depends on the external load, since it is significantly deformed under its influence. However, these deformities are short-term. A true wealth of forms lies in the repetition, combination and alteration of all the basic forms of tensile structures, and as a result, a practically innumerable number of different structures can be obtained.

4.2. Form finding

The simplest membrane structures must have at least four points of support [1]. This is a consequence of their form being doubly curved with a negative Gaussian curvature. As is known, any three different points in space define a plane. Thus, a membrane structure defined by three points would be planar. This shape of a membrane would not be unstable, quite the opposite. With the introduction of prestressing, the membrane would assume the shape of a minimum surface, that is, an area with minimum potential energy, which means that the internal forces would be in equilibrium, and the structure would be stable. However, a problem would appear during the effects of external loads. Much has been written on how extensive deflections represent one of the greatest problems concerning tensile structures. The plane form, obtained through three points of support, would have a significantly smaller resistance to deflections in comparison to the saddle form. This problem of the membrane structure is analogous to the problem of the singularity which is present even among other structures in civil engineering. In its simplest form, it is a collinear beam with a hinge in the middle. It is because of this that the planar form is not treated as one of the possible forms of tensile structures. It is necessary then to use at least four points of support. At the same time, an additional condition is made, and that is that these points in the geometric sense cannot be in one plane. The connection of these points results in a spatial form which is doubly curved, and with a negative Gaussian curvature. These kinds of forms are similar to a hyperbolic paraboloid, and are often referred to as saddle forms. A further increase in the number of points of support is possible, where the condition that they are not all in one plane must always be adhered to.

The potential forms of membrane structures can further be expanded through the introduction of linear supports. Both straight and curved supports are used. By using one straight and one point support, we once again obtain a plane form which is not acceptable in practice. Acceptable forms are obtained through the use of two linear supports that are not in one plane, or one straight and two point supports which are not on the same plane, or one curved and two point supports which are not on the same plane, etc.

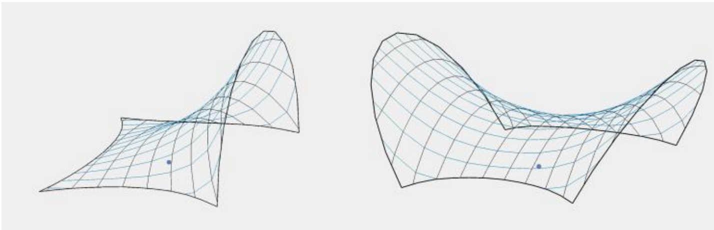


Fig. 6 The forms obtained through the use of one curved and two point supports (left), and two curved supports (right)

4.3. The relationship between form, function and structural material

The form and the applied structural material have a decisive influence on the appearance and functionality of the structure. Bridgens and Birchall [3] studied this relationship and some of the results of their work will be analyzed in this paper. Their work was carried out on three models, where the height of the model and the material characteristics varied, and the results were compared in order for conclusions to be drawn. These models represent membrane structures of the saddle and cone forms.

Fig. 7 The studied forms

The study was carried out using the Oasys software which is specialized for this type of structure. Two cases of load were calculated, snow load with an impact of 0.6 kN/m2 and wind with a suction impact of 1.0 kN/m2. In the first part of the case study, the authors varied the height of the hyperbolic paraboloid and monitored how that change referred to the other parameters of the structure. The results of the maximum deflection and membrane forces were analyzed. In addition, the characteristics of the material also varied, including the elasticity modulus E and the shearing modulus G.

On the basis of their results, it is possible to derive the following conclusions. First and foremost, an increase in the curvature of the structure has a positive influence on the decrease in the maximum deflection under external load. The increase in the shearing modulus also decreases the maximum deflection. The increase in the curvature and the shearing modulus also leads to the reduction in the membrane forces under external load. The same effect on the force and deflection is achieved through the increase in the elasticity modulus. It is also noticeable that in the case of the increase in the curvature, significant differences occur by the ratio between the height and length of the side of 0.5. A further increase is used to achieve a very small decrease in force and the deformation, but the structure loses its functionality due to excessive height and curvature. We can thus conclude that 0.5 is the optimum relation between the height and length of the side in the case of the hyperbolic paraboloid.

The following part of the case study refers to the study of the cone form. In the case of this model, both the height of the model and the diameter of the opening varied. The influence of the changes in these parameters of the membrane on force and deformation was studied. In addition to changes in the geometry, the models with various values of the elasticity modulus were also tested.

The results clearly indicate that it is of key importance to select the optimum relationship between the height of the structure, the diameter of the opening and the length of the side. Otherwise, various unwanted structural effects occur, such as the pilling of snow and the occurrence of great deformations. In addition, it was proven that an increase in the diameter of the opening results in the decrease of the membrane forces in the structure, which can also be considered favorable. Nevertheless, here it is also important to determine the right relationship, since the design of a great opening leads to the non-functionality of the structure. Finally, an increase in the elasticity modulus in the case of cone membrane structures leads to a non-linear increase in the tensile force in the structure under the influence of external load.

We can finally conclude that forms with higher curvature, up to a certain extent, are more suitable for membrane tensile structures, irrespective of the type of applied form. At the same time, even the characteristics of the structural material are of great importance for the value of the maximum deflections and membrane forces under the influence of external forces.

5. An Analysis of Some of the Most Significant Objects Designed Using the Tensile System

5.1. The Olympic stadium in Munich

The Olympic Stadium in Munich [7] is one of the most significant architectural works of the 20th century. It was built for the Olympic Games in 1972. It was at the same time the first sports object covered with a tensile structure. In addition to the stadium, the pool, gymnastics hall and all access roads were covered in a similar fashion, which finally amounted to an area of approximately 74000 m2. The open competition for the design of sports facilities for the Olympic Games was announced in 1967. The German constructionist Otto Frei won the competition with his design.

Construction on the winning design began, but later underwent many changes. One of the basic ideas was for the structural material to be a PVC membrane, but it turned out to be impossible to cover such an extensive area without an increase in the number of masts. The second reason was that using a cable net structure covered with acrylic glass allowed better lighting for the stadium, which was more convenient for televising matches. In addition, it was not possible to use only one continuous surface, and so it was divided into a sequence of segments. The position of the surface was altered, so that it did not stretch over the top of the masts. Instead the masts intersected it, which contributed to the decrease in the concentration of forces. The idea of using the same structure to cover all the facilities was realized. The time needed to finish construction on this object was 4 years. The cover of the stadium consisted of 9 segments. These segments were not identical, even though they were very similar. Namely, all of the structure elements were of the same type, but of different dimensions. Today such an object would probably be characterized as irrational, since the typization of the elements would decrease the overall cost and construction time. During construction, the rationale was different and the argument was that the object would be built as an experimental one, since it needed to prove the justifiability of the use of tensile structure and to test their success as parts of sports facilities, as a result of which the invested funds were not of primary importance.

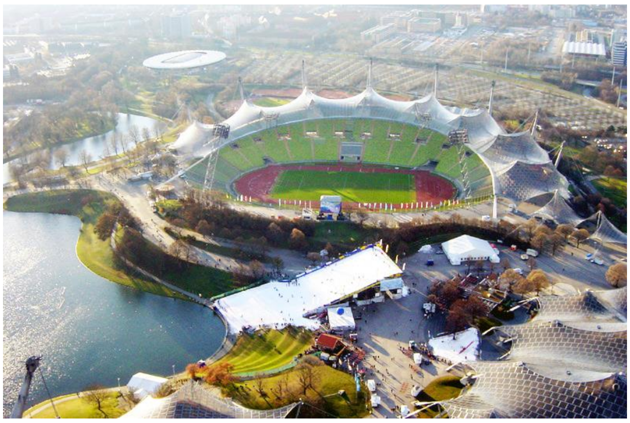


Fig. 8 The Olympic Stadium in Munich

The situation could be compared to the Olympic Games held six years ago in China, which is the second greatest economic power in the world, and where the swimming pool area and the stadium were also built as experimental designs. However, cost was a main concern, and thus the elements were typified. The elements used in Munich for each segment are the mast, the flying mast, the edge and stabilizing cables and a network of steel ropes. The static system was inventively designed so that the use of a flying mast rendered it unnecessary to use internal masts which would impair the view from the seats. Each of the segments individually is unstable, but through their connection in the structure, stabilization is achieved in a transversal direction. In the radial direction, the structure is balanced by an extensive tensile cable with a length of over 300 m. The network of steel cables is doubly curved with a negative Gaussian curvature and has the shape of a hyperbolic paraboloid. That is the element which is most deserving of the architectural impression which the stadium creates. The wavy biomorphic form fits in ideally with the ambient of the park in which it is located. The cables intersect so that they form a field which is 75x75 cm in size, and they were covered with acrylic glass 2.9x2.9 m in size. The network grids could have been bigger, but the dimension which guaranteed that none of the workers would accidentally fall and jeopardize their safety was selected, and the goal was achieved. The masts represent an important structural, but also esthetic element. They are made of steel and have a height of 80 m. They are exposed to pressure, unlike all the other elements of the structure. Their function is to provide supports for the cover. Visually we can determine an analogy between the cover of the stadium which hangs from the masts and a spider's web. During the design process there was no software that could be used to calculate the effect of external forces on the structure. The only computer assistance which the designers could count on was the software which helped determine the geometry, that is, the shape of the cover. Models in a scale of 1:125 were used to test loads and calculate the intensity of the force of prestressing, which is necessary for tensile structures and for achieving stability. The production process was carried out by the prefabrication of elements, their connection to the ground and their positioning on predetermined locations, and prestressing. The calculation allowed an error of 15% during the prestressing, but it turned out that it was much smaller. The most deserving for the structure calculations were engineers Schlaich and Frei. It is important to point out that prior to tensile structures, the most modern structure system was the concrete shell. The shells brought possibilities that had not been imagined to date since they spanned more than several tens of meters with a thickness of less than 10 cm. Then came the tensile structures which offered even longer spans, with an even smaller cross-section, and at the same time were transparent. Tensile structures today give the impression of being exceptionally lightweight, even feather-weight structures, and 40 years ago this impression had to have been even more pronounced. Adding to all that the attractive doubly curved form they have, tensile structures have ensured a place in the construction practice of the future. The Olympic Stadium in Munich was a pioneer endeavor which today could be said to have set the cornerstone for the application of tensile structures in sports and other public facilities over the world. During design and construction there was much criticism aimed at the stability and duration of the structure. Doubt in this respect turned out to be quite without merit. Even today, after more than 40 years, the structure of the cover of the stadium in Munich is completely stable and safe. It is in excellent condition and is regularly submitted to testing. It still represents a tourist attraction and is one of the most significant landmarks of Munich.

5.2. The cover of the central court at Wimbledon

The central court in Wimbledon [8] was built in 1922 and covered only one segment of the seats. This cover was completely replaced in 1992, but a part of the seats and the field remained uncovered. Due to frequent rain which interrupted the tournament, the idea to cover the entire object was born. The conclusion was reached that it would be best to build a mobile roofing structure. After the completion of the tournament in 2006, the cover was removed and work began on a new roof. A tournament was played for the first time in 2007 on the central court without any cover. The stationary part of the cover was completed in 2008. The complete cover for the stadium was officially put into use in 2009, including the mobile part. This court was used during the 2012 Olympic Games.

As the structure most conducive to the needs of this object, the tensile structure was combined with steel girders. These girders have one bottom and two upper sets of members, which are interconnected diagonally. The upper members are slightly curved, so that the drainage is natural. There are 10 identical girders that span 77 m. They were placed on tracks, have wheels which move along them and are set into motion by hydraulic mechanisms, functioning with a precision of 1 mm. The lowest point of the structure is located at a height of 16 m, so the game is not compromised, not even in the case of high balls. The membranes were constructed out of the most modern fiberglass covered in PTFE, and cover a surface of approximately 5200 m2. They are set up between each two neighboring grids and folded in the middle when the roof is open. Even then they are susceptible to tensile forces. Two types of membranes were used, which differ in terms of the percentage of light they filter through. The ability of the membranes to allow a great deal of natural light in led to the tensile structure being used as a cover. This allowed the possibility for avoiding the use of artificial lighting, and so the conditions for playing and watching tennis are almost identical to those when the game is played under an open roof. The used membranes have the ability to filter in 40% of the light, and were carefully distributed so that the light which fell on the court was completely diffused and there were no shadows. The warranty period for these membranes given by the manufacturer is 15 years.

Fig. 9 The cover of the central court in Wimbledon

The structure was designed to include the effect of wind speed of 70 km/h. The roof was divided into two parts, so that it can be opened independently and closed on each side. When it is closed, in the middle the girder carriers meet on both sides, and between them there is no membrane, due to the fact that they fully merge. The roof closing process lasts approximately 10 minutes, which could be considered relatively fast. In the facility, the ventilation systems and systems for the regulation of air humidity were installed, so that the interior is independent of any external climatic conditions. The supporting structure of the retractable roof was made of steel. Due to the smaller size of this structure in comparison to the previous one, it was possible to add 6 more rows of seats at the top, which increased the overall capacity by 1200 seats which is now 15000. The weight of the newly built cover is approximately 3900 tons. The overall cost of the cover was approximately 120 million Euros. The project manager was the HOK design company, but many other companies were included in the design and construction process due to the complexity of the project. In addition to the construction process which lasted for three years, the process of preparing the project documents was very long. Alternative solutions were first tested using software, and then models built to scale were tested for various influences. The cover of the central court at Wimbledon showed in this paper is characterized as the representative of the group of structures which are retractable. If this system were to be used more frequently, it would bring significant advantages for the objects; however, its greatest disadvantages were the large cost of construction and maintenance. That is why it is rarely used, and exclusively for exceptional objects.

5.3. The stadium in Durban

The stadium in Durban is also known as the Moses Mabhida and was built for the 2010 Football World Championship. It represents the most spectacular stadium of this championship. A hybrid structure system that was the result of a combination of up to three systems was used, including a supporting arch, hanging and tensile system. The stadium was built in only two and a half years.

Fig. 10 The stadium in Durban

The size of the stadium without the arch is 320x280 m, and its height in its highest part is 45 m. Even though the stadium does not have an athletic track, the seats were positioned in an elliptical shape. The stadium capacity during the World Championship was 63000, but was later reduced to 54000 seats. The standings are made of reinforced concrete and are independent of the structure of the cover. They consist of a ground floor and two galleries. The seats on the ground floor and the lower gallery were painted using various colors. Thus, even if the stadium is not seated to its full capacity, there is the visual impression that there are no empty seats. In the higher gallery there are seats colored white, which fits with the design of the cover of the seats. The main characteristic of this stadium is the steel arch which spans across the axis of the stadium. The range of this arch is an imposing 340 m and its height is 106 m. The stability of the arch is provided by the south side of the arch splitting into two parts. The distance between the supports is 60 m. These two parts of the arch are interconnected by beams for better stability. The inspiration for this type of arch was the history of that nation which had at one point been separate, but is now united. A similar motive can be found on the flag of the Republic of South Africa. All three points of support were constructed as if they were fixed supports. With this structural solution, the arch became a spatial figure with three supports that are not collinear, which means that it is completely stable. The dead load that affects the arch is symmetrical. In addition to the self-weight of the arch, the arch is also affected by the tensile forces of the cables which bear the weight of the structure. This kind of load causes compression of the arch, which is the most appropriate kind of influence on arch structures. The cross-section of the arch is a hollow box, 5x5 m in size. The arch was designed as prefabricated, and consists of 56 segments 10 m in length, which were put together on site. The overall weight of the arch is 2600 tons. The erection of the arch was especially complicated, and required a very high degree of precision. The elements of the arch were positioned at the same time on both sides. During the construction process of the arch, temporary scaffolding had to be built. Only after it was constructed and the last segment, weighing 60 tons, was placed at the very top of the arch did the arch become stable and independent of its temporary supports. The construction of the arch lasted almost 9 months. Using cables with a diameter of 95 mm, the tensile structure was placed onto the arch. The relationship between the cables and the arch was established in places where the elements of the arch were interconnected. The weight of the used cables is 700 tons, and their length is 17 km. The membrane subtype of the tensile structure was used. The membranes are made of PTFE and there are 208 of them. They cover 88% of the seats or approximately 46000 m2. Up to 50% of the light is filtered in. The order of the supports is such that the membranes have a saddle shaped form, and the entire structure looks like it is folded, and so from a distance it may seem like it was made of reinforced concrete. On the external side, the textiles are bound by a compression ring. The outer ring is 880 m in length. It rests on over 100 masts which are tilted outwards. Between them there are a total of l 550 aluminum profiles at a small distance, which form a transparent and open facade. The overall surface of the facade is approximately 15000 m2. The stadium resembles the Wembley stadium due to the inclusion of a huge arch. Only a few years after the construction of the arch in London, with a range of 317 m, certain progress was made in civil engineering, so it was possible to build an even bigger arch. To this day this object has represented the best that civil engineering has to offer in the case of arch structures. In Durban, unlike London, a box and not a girder profile of the arch was used. The structure of the cover is much simpler and is lighter than the one in London. The only drawback to the stadium in Durban is the fact that the arch throws a shadow onto the pitch. Even though the arch is high and the shadow is diffuse, it might still be undesirable for games played during the day. Understanding the potential of this imposing architectural edifice, the owners daily organize a series of activities for the visitors to the stadium. One of them is a tour to the top of the arch, to which a funicular leads. The stadium in Durban represents a very good example of how it is possible to combine the facade of the stadium, structural elements of the cover, and the cover itself. As the main structural element, the arch is also dominant in a visual sense. However, even though they are unassuming, the facade and the cover play an important role in determining the architectural identity of this building. The unimposing nature is achieved through the numerous repetitions of elements, and in the case of the cover, the repetition of form. This is how the dominance of the arch is enhanced and emphasized.

6. CONCLUSION

Tensile structures are usually used to cover sports fields and public areas, covering large areas using a minimum amount of material. Their advantages are two-fold. Esthetically, they are very attractive as they come in unusual curved forms, and allow the light to come in. Construction wise, tensile structures have an advantage over other structural systems because of their lightweight nature, which is a result of the fact that in the structure there are no moments of bending and compression forces. For that reason tensile structures were used in many important objects over the world. However, they also have certain shortcomings which need to be taken into consideration in order for them to be used successfully. Their biggest drawback is their poor thermal resistance, which is a consequence of the thickness of the structure. In addition, these structures are very susceptible to great deformations under the influence of external load. What sets tensile structures apart from other structural systems are their structural materials, but also their design and construction process. As one of the most recent and most promising structural systems, tensile structures offer many possibilities for further research and improvement.

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ŠATORASTE KONSTRUKCIJE KAO NAJNAPREDNIJE LAKE PROSTORNE STRUKTURE

U radu su analizirane formalno estetske karakteristike objekata savremenih studentskih domova. Fokus istraživanja je na specifičnim karakteristikama oblikovanja forme i obrade fasada objekata studentskih domova. Uočeno je i istraženo nekoliko tendencija savremene arhitekture primenjivanih u projektovanju studentskih domova: reciklaža "starih formi", primena mustre, avangardnost i eksperimentalnost u dizajnu i "nova modularnost".

Ključne reči: *šatoraste konstrukcije, membrane, dvostruko zakrivljena forma, zategnute konstrukcije, lake prostorne strukture*