International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2011
E. Oñate, B. Kröplin and K.-U.Bletzinger (Eds)

TENSEGRITY RING FOR A SPORTS ARENA FORMFINDING & TESTING

Diana Peña*, J. Ignasi Llorens†, Ramon Sastre†, Daniel Crespo† y Joshua Martínez†

* PhD. Student Universidad Politécnica de Catalunya - Av. Diagonal 649 CP.08028, Barcelona-Spain
diana.maritza.pena@estudiant.upc.edu

† Prof. UPC ignasi.llorens@upc.edu, † Prof. UPC ramon.sastre@upc.edu, † Prof. UPC daniel.crespo@upc.edu, † Prof. UPC joshua.martinez-tristancho@upc.edu

Key words: Tensegrity ring, formfinding, diamond pattern, double layer, pretension, wind tunnel, pressure coefficient.

Abstract. The current prototype's key contribution to the field of light-weight structures is that it is the first time that a pure tensegrity ring has been used in place of a compression ring.

This design features a cladding structure for a sports arena, which consist of a ring-shaped outer section and a central roof structure. The ring-shaped outer section of the stadium consists of a tensegrity structure, which uses textile membranes in a place of conventional tension cables to bear the tensile forces occurring between the pressure elements. The supporting framework and spatial enclosure therefore become one an extension to the tension integrity principle. The central area of the roof is covered over by a Geiger dome, which in turn is a specific version of the tensegrity principle.

1 FORMFINDING

Figure 1: Tensegrity ring diameter Ø 40 cm. (above) - Tensegrity ring diameter Ø 100 cm. (below) - Models scale 1:100

The ring structure is made up of a continuum of ten upper-level paraboloids and ten lower-level paraboloids with a diameter of 40 cm. Formfinding for the ring structure is generated by

means of a diamond-shaped membrane pattern pieces (rhombus = major axis 11.5 cm, minor axis 4 cm) formed by two layers of twenty bars (L=20 cm), which are arranged either in an oblique or a diagonal position. The bars are connected to the end points of the membrane as shown in Fig 2 and then to the adjacent membrane piece at the corresponding end point.
This procedure is repeated for all adjacent membrane pieces, while at the same time, the upper section is interlaced with the lower section creating one continuous ring structure when the last two bars are put into place.
A dome is created by combining the above ring structure with a “roof” consisting of one central mast (L=9 cm) and ten minor masts (L=6.5 cm) placed in a circular form held in place by the tension of the membrane itself. The membrane balances the system and joins the dome with the tensegrity ring. The final structure is a dome free of any internal supports.

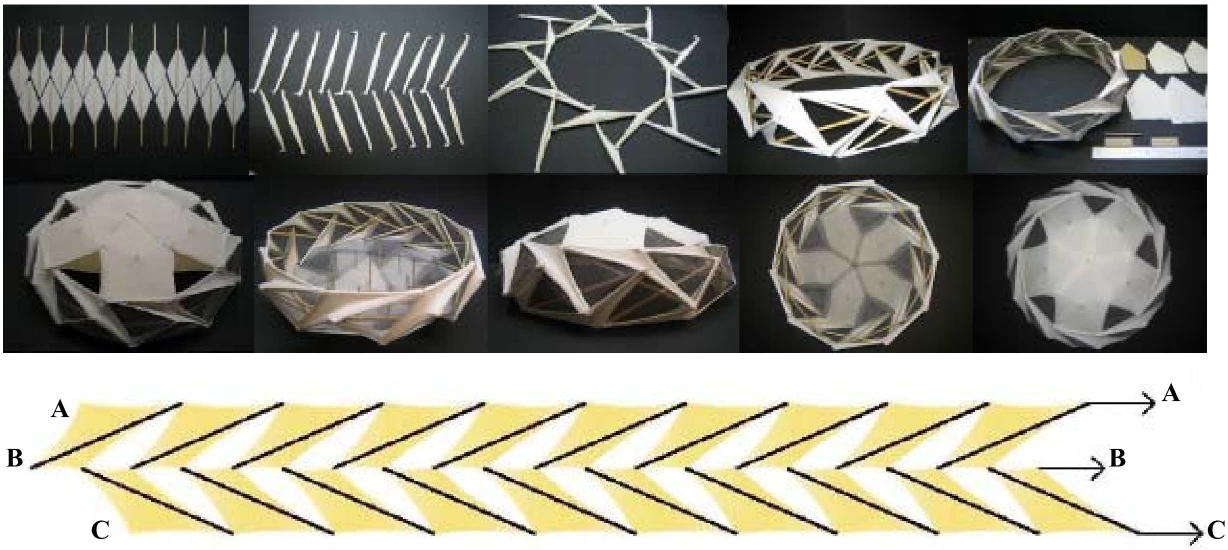


Figure 2: Photos showing the components and final structure as well as a diagram of the tensegrity ring construction method to created a dome in pure tensegrity Ø 40 cm. - Model scale 1:100

2 TESTING

The proposed structure was tested using several methodologies:
Software testing (Wintess), physical testing (wind tunnel), qualitative analysis (physical model).

2.1 Software testing

The proposed structure was first tested against wind and snow loads via WinTess [1] software. Testing demonstrated the following:

- During extreme external wind conditions of 170 km/h, the maximum inward (horizontal) displacement of the bar free nodes is 100 cm, which was decreased by 20% after being reinforced. (The bar free nodes are located on the side of the structure between the upper and lower levels of the tensegrity ring. They are not directly connected to the upper dome or to the foundation nodes).
- It allowed the structural elements (membrane, tubes, and cables) to be analyzed and optimized for dimensional stability.

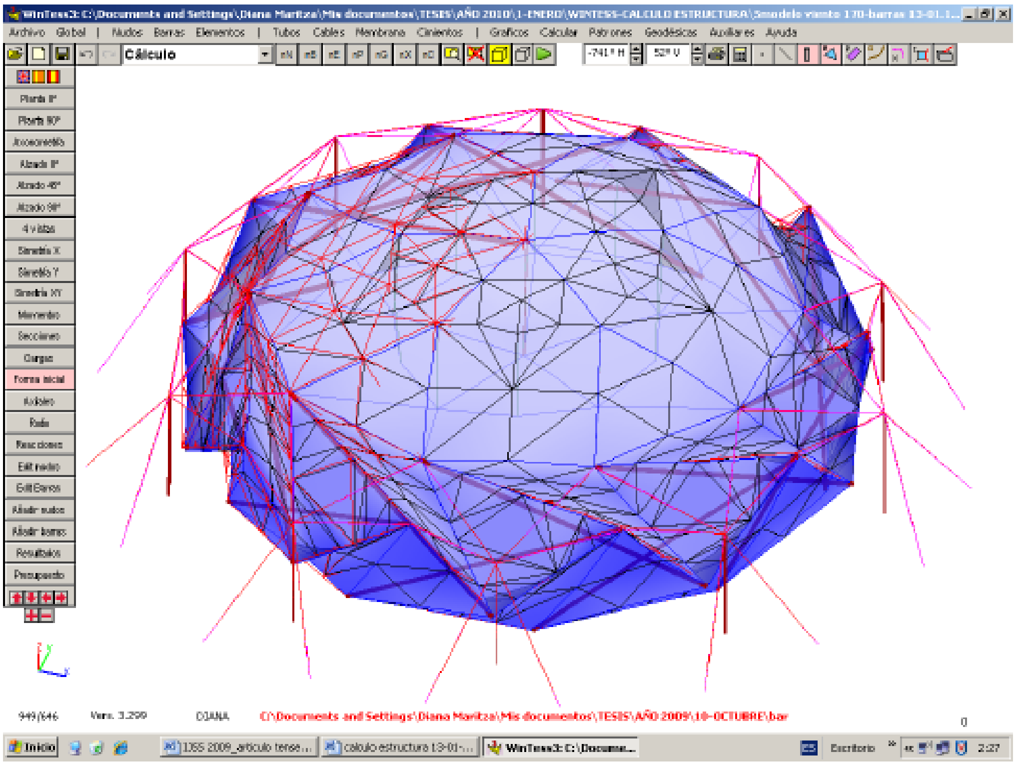


Figure 3: Structure in equilibrium when wind up-to 170 km/h is applied. Note that the computer model is shown with both the membrane and cables, which prevent the structure from moving in the real world.

- The exterior tubes are placed surrounding the ring so that they continue in the direction of the forces coming from the top membrane dome. The pretension cables increase the stiffness of the structure and contribute to support and balancing of the system.
- The structure is closed, in equilibrium, and able to support its own weight.
- The large displacements must be countered by the use of external tubes and cables if the structure is to be built in the real world.
- During external snow loads of 50 kg/m, a maximum (vertical) displacement of 60 cm is found in the minor dome masts and the maximum reaction in the foundation nodes is 22 tons.

2.2 Physical testing

The proposed structure was then tested in a wind tunnel at UPC in Barcelona using a rigid model made by a three dimension printer.

Due to the nature of tensile-textile construction (lightweight structures), the ability of the structure to withstand external loads relative to weight of the structure itself is much greater that of conventional construction [2]. It is important to note, though, that small changes in wind pressure or snow loads can have a major impact on the size and shape of the structural elements and the deformations that occur. For this reason, it is necessary to understand the pressure and suction coefficients that impact the structure: vertical force (lift coefficient) and horizontal force (drag coefficient).

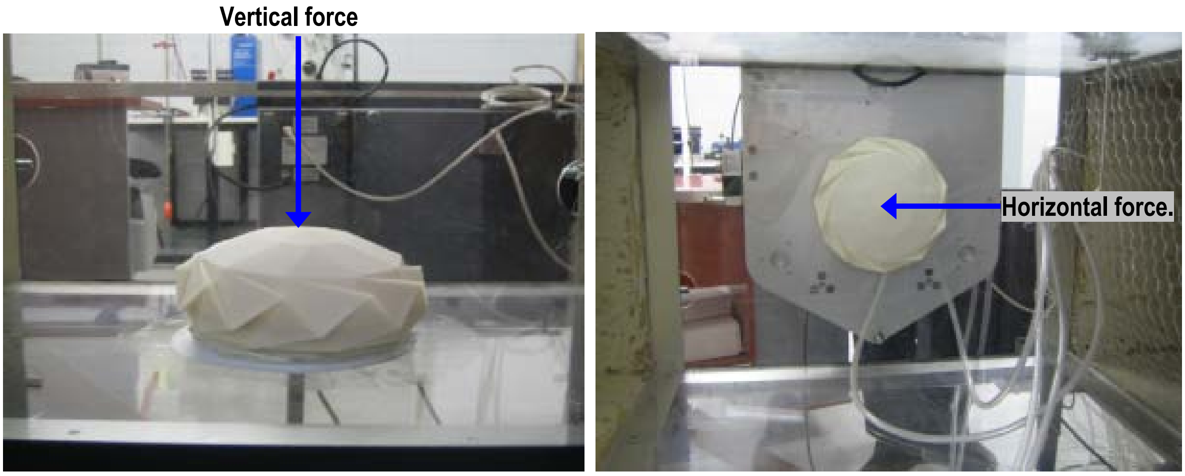


Figure 4: Vertical force (lift), horizontal force (drag)

Wind tunnel	Lift & Drag Coefficients
The wind tunnel is open, and works by aspiration (Eiffel style); that is, undisturbed air is accelerated through a nozzle, due to pressure difference and sent to the model; thus the flow profile is laminar. However, the model size is 0.17 m, and free stream speed was ranged between 5 and 20 m/s, that is Reynolds numbers from 5x10^4 and 2x10^5, which is a fully turbulent regime, as corresponds to the real size building. **The model is** rigid, made in a plastic material, while the real size cover is flexible. The forces measured on the scale model have been scaled to the real size building assuming that it acts as a rigid body, due to the beams that support the building in tension. **The wind tunnel tests** were used to determine the lift (vertical force) and drag coefficients (horizontal force). Drag coefficient was used in WinTess to calculate the structure to wind up-to 170 km/h. 	The value of the global lift coefficient obtained from the experimental measurements was Cl ~0.86. Local measurements of the lift coefficients, determined in small holes on the model surface, reach values up to 1.5. Given the size of the wind tunnel testing section (40 cm x 40 cm cross section) and the diameter of the model (17 cm) the statistical error is estimated to be approximately 15%. Where Fvertical is the vertical component of the force acting on the model, r is the air density and v is the free stream speed. $C_l = \frac{2F_{vertical}}{\pi\cdot(7.5\,cm)^2\cdot\rho\cdot v^2}$ (1) Testing showed that there is a -0.3 global Cp pressure drag coefficient (suction). Local pressure coefficients show a significant dispersion. This negative Cp is the result of the very aerodynamic convex forms, which allow the wind to pass by freely. $C_d = \frac{2F_{drag}}{\pi\cdot S_e\cdot\rho\cdot v^2}$ (2) Where Se is the elevation surface (model 0,008718 m2)

Table 1: Wind tunnel testing - Lift coefficient & drag coefficient.

2.3 Qualitative analysis

A 100 cm diameter model was built to perform qualitative testing. To make the larger prototype, there were two options: First, the quantity of bars would have to be increased proportionally to the elasticity of the membrane used. Second, if the length of the bars is increased, the ring diameter will be larger. A larger prototype was assembled using 20 struts (Length=50 cm) in a double layer resulting in an overall diameter of 100 cm. The ratio of length of the bars to the overall diameter is 1:2.

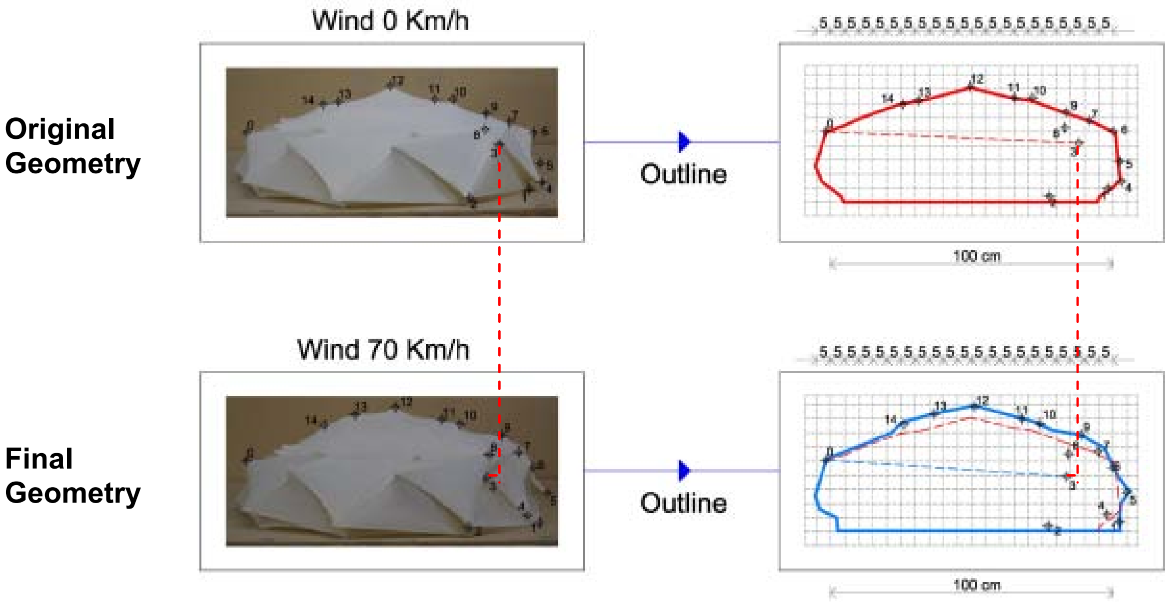


Figure 5: Model scale Ø 100 cm. An 80 cm-diameter fan was used to simulate a 70km/h wind.

In the first sample, we can observe the original geometry. In the second, we see the final geometry that was tested and the largest displacement was observed at point #3, which was 5cm.

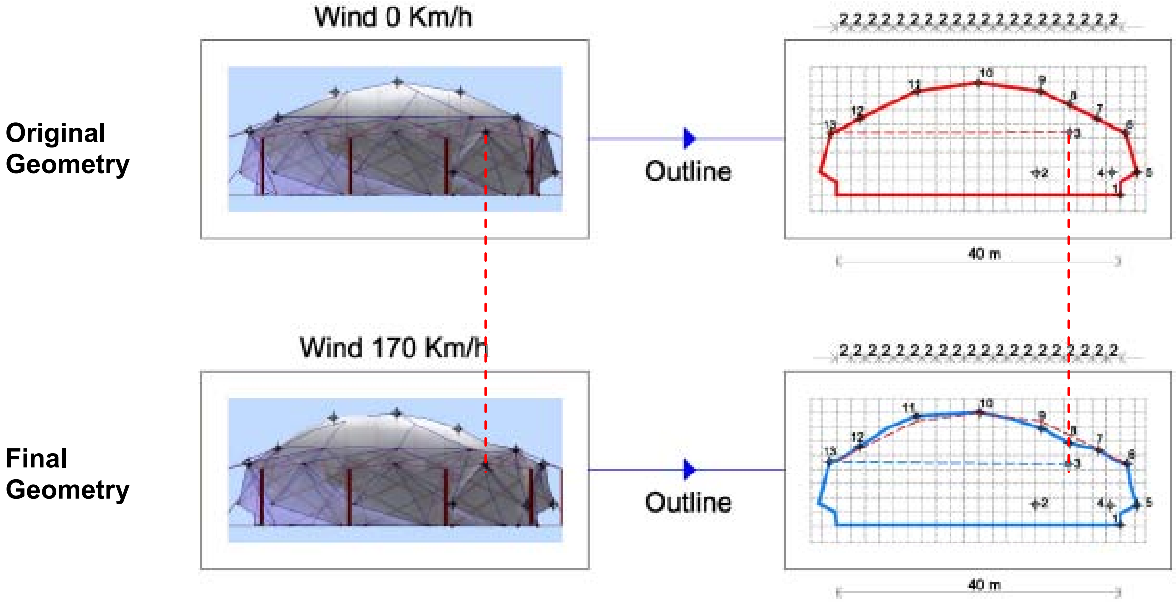


Figure 6: Comparative analysis – Wintess software.

In the second sample, the model was tested with WinTess. It is important to note that for the qualitative analysis, the prototype was only built with membrane, while in WinTess analysis, the structure was built with the addition of cables. For this reason no displacement was observed in point #3 of the final geometry. The qualitative-analysis-optimized structure is shown along with the software-optimized structure. The results show that they are very similar, which validates the testing methods and model.

3 RESULTS

After wind-tunnel testing (pressure coefficients) and qualitative analysis, we found that there was an overload of forces on the model and we had to re-optimize the structural elements using WinTess software to construct a model of a structure for the real world.

Structural characteristics of the 40 m WinTess real-world model elements:

- **Membrane:** Ferrari Fluotop T2 1302 - **Prestress** 0.8 % = 32,6 daN/5cm = 652 kg/m **Resistance** Rk = 800/700 daN/5cm = 16000,0 kg/m - **Safety factor** (5) = Rd = Rk / 5 = 160 daN/5cm = 3200 kg/m
- **Border cables (Boltrope):** WS-2 (36mm) Galv ∅ 36 - **Section** 855 mm2 - **Elasticity modulus** 1.635 t/cm2 = 163,5 kN/mm2 - Q= 125,46 t = 1.254,6 kN
- **External cables (Guyrope):** WS-2 (36mm) Galv ∅ 36 - **Section** 855 mm2 - **Elasticity modulus** 1.635 t/cm2 = 163,5 kN/mm2 - Q= 125,46 t = 1.254,6 kN
- **Ring tubes:** L=20 m - ∅ 400-10_S235 - **Section** 122,522 cm2 - **Elasticity modulus** 2.100 t/cm2 = 210 kN/mm2 - **Density** 7,85 t/m3 = 78,5 kN/m3
- **Dome central mast:** L=9 m - ∅ 110-5_S235 - **Section** 16,493 cm2 - **Elasticity modulus** 2.100 t/cm2 = 210 kN/mm2 - **Density** 7,85 t/m3 = 78,5 kN/m3
- **Dome minor masts:** L=6,5 m - ∅ 90-4_S235 - **Section** 10,807 cm2 - **Elasticity modulus** 2.100 t/cm2 = 210 kN/mm2 - **Density** 7,85 t/m3 = 78,5 kN/m3
- **External tubes:** L= 8 m - ∅ 250-8_S235 - **Section** 60,821 cm2 - **Elasticity modulus** 2.100 t/cm2 = 210 kN/mm2 - **Density** 7,85 t/m3 = 78,5 kN/m3

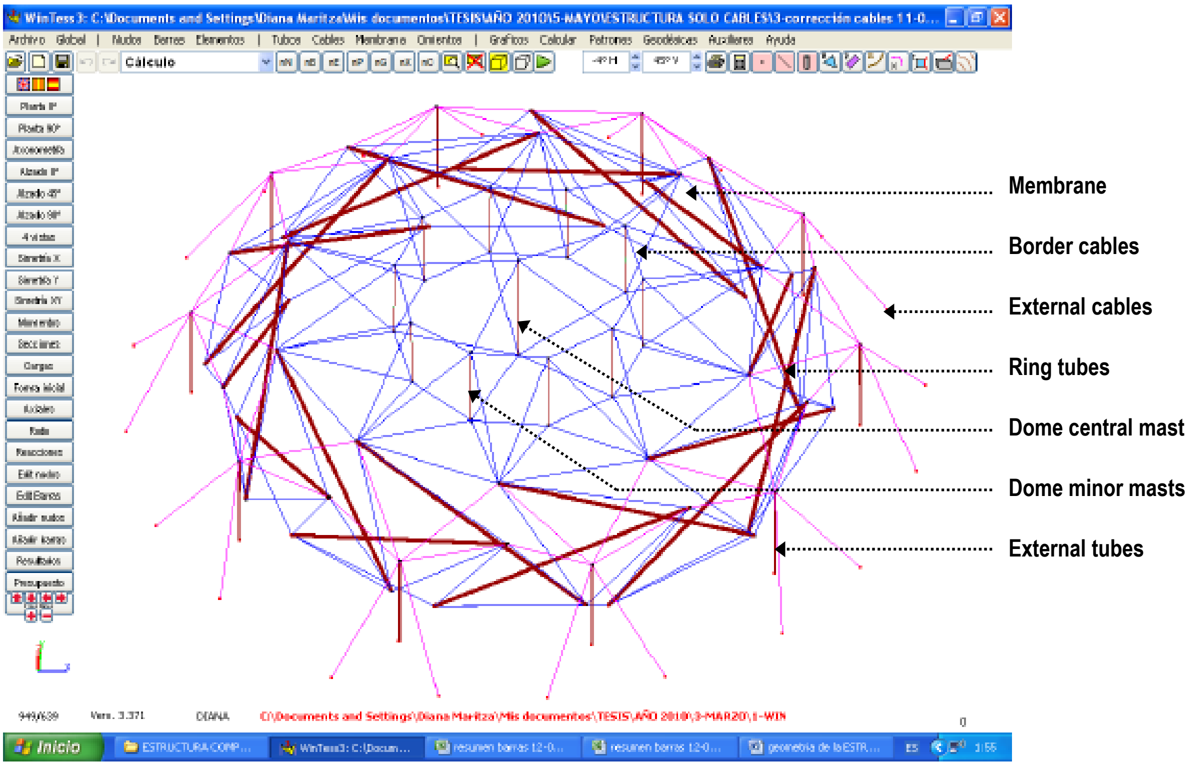
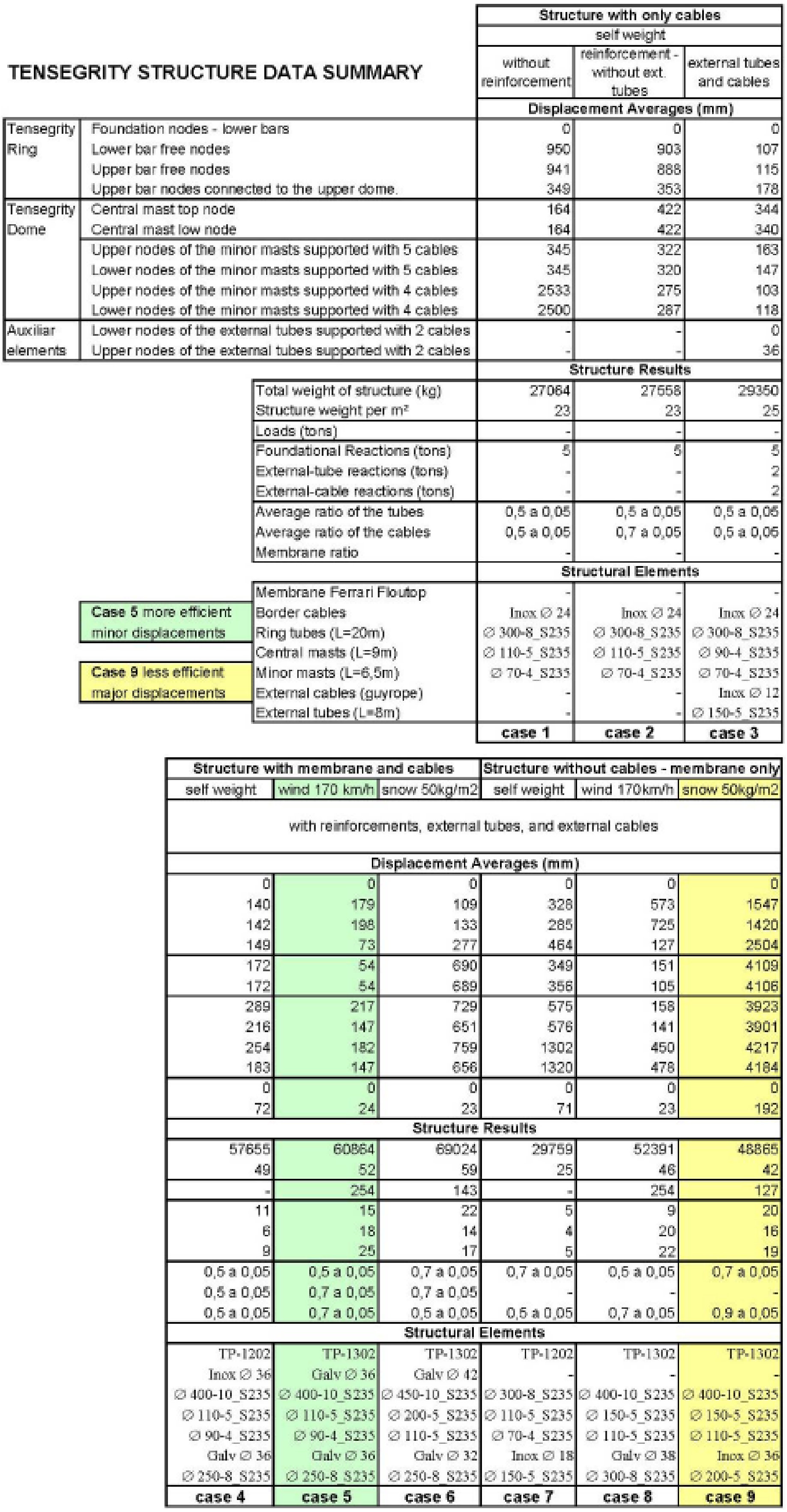


Figure 7: Model-elements structural characteristics.
Total weight = 69.023 kg – Weight/m2 = 58 kg – Maximum reaction in foundation nodes 24 ton.



TENSEGRITY STRUCTURE DATA SUMMARY

		Structure with only cables			Structure with membrane and cables			Structure without cables - membrane only		
		self weight			self weight	wind 170 km/h	snow 50kg/m2	self weight	wind 170km/h	snow 50kg/m2
		without reinforcement	reinforcement - without ext. tubes	external tubes and cables	with reinforcements, external tubes, and external cables					
		Displacement Averages (mm)								
Tensegrity Ring	Foundation nodes - lower bars	0	0	0	0	0	0	0	0	0
	Lower bar free nodes	950	903	107	140	179	109	328	573	1547
	Upper bar free nodes	941	888	115	142	198	133	285	725	1420
	Upper bar nodes connected to the upper dome.	349	353	178	149	73	277	464	127	2504
Tensegrity Dome	Central mast top node	164	422	344	172	54	690	349	151	4109
	Central mast low node	164	422	340	172	54	689	356	105	4106
	Upper nodes of the minor masts supported with 5 cables	345	322	163	289	217	729	575	158	3923
	Lower nodes of the minor masts supported with 5 cables	345	320	147	216	147	651	576	141	3901
	Upper nodes of the minor masts supported with 4 cables	2533	275	103	254	182	759	1302	450	4217
	Lower nodes of the minor masts supported with 4 cables	2500	287	118	183	147	656	1320	478	4184
Auxiliar elements	Lower nodes of the external tubes supported with 2 cables	-	-	0	0	0	0	0	0	0
	Upper nodes of the external tubes supported with 2 cables	-	-	36	72	24	23	71	23	192
		Structure Results								
	Total weight of structure (kg)	27064	27558	29350	57655	60864	69024	29759	52391	48865
	Structure weight per m²	23	23	25	49	52	59	25	46	42
	Loads (tons)	-	-	-	-	254	143	-	254	127
	Foundational Reactions (tons)	5	5	5	11	15	22	5	9	20
	External-tube reactions (tons)	-	-	2	6	18	14	4	20	16
	External-cable reactions (tons)	-	-	2	9	25	17	5	22	19
	Average ratio of the tubes	0,5 a 0,05	0,5 a 0,05	0,5 a 0,06	0,5 a 0,05	0,5 a 0,05	0,7 a 0,05	0,7 a 0,05	0,5 a 0,05	0,7 a 0,05
	Average ratio of the cables	0,5 a 0,05	0,7 a 0,05	0,5 a 0,06	0,5 a 0,05	0,7 a 0,05	0,7 a 0,05	-	-	-
	Membrane ratio	-	-	-	0,5 a 0,05	0,7 a 0,05	0,5 a 0,05	0,5 a 0,05	0,7 a 0,05	0,9 a 0,05
		Structural Elements								
	Membrane Ferrari Floutop	-	-	-	TP-1202	TP-1302	TP-1302	TP-1202	TP-1302	TP-1302
	Border cables	Inox ∅ 24	Inox ∅ 24	Inox ∅ 24	Inox ∅ 36	Galv ∅ 36	Galv ∅ 42	-	-	-
	Ring tubes (L=20m)	∅ 300-8_S235	∅ 300-8_S235	∅ 300-8_S235	∅ 400-10_S235	∅ 400-10_S235	∅ 450-10_S235	∅ 300-8_S235	∅ 400-10_S235	∅ 400-10_S235
	Central masts (L=9m)	∅ 110-5_S235	∅ 110-5_S235	∅ 90-4_S235	∅ 110-5_S235	∅ 110-5_S235	∅ 200-5_S235	∅ 110-5_S235	∅ 150-5_S235	∅ 150-5_S235
	Minor masts (L=6,5m)	∅ 70-4_S235	∅ 70-4_S235	∅ 70-4_S235	∅ 90-4_S235	∅ 90-4_S235	∅ 110-5_S235	∅ 70-4_S235	∅ 110-5_S235	∅ 110-5_S235
	External cables (guyrope)	-	-	Inox ∅ 12	Galv ∅ 36	Galv ∅ 36	Galv ∅ 32	Inox ∅ 18	Galv ∅ 38	Inox ∅ 36
	External tubes (L=8m)	-	-	∅ 150-5_S235	∅ 250-8_S235	∅ 250-8_S235	∅ 250-8_S235	∅ 150-5_S235	∅ 300-8_S235	∅ 200-5_S235
		case 1	**case 2**	**case 3**	**case 4**	**case 5**	**case 6**	**case 7**	**case 8**	**case 9**

Case 5 more efficient minor displacements

Case 9 less efficient major displacements

Table 2: A comparison of the results between structure with only cables, structure with only membrane and structure with both membrane and cables.

In the analysis (Table 2) we can compare the different results of the model with different options through the WinTess software. The nodes displacements in the tensegrity ring and the dome, the weight of the structure, reactions, dimension of the structural elements. All tested under loads of wind, self weight and snow take in account the pressure coefficient. The comparison between structure with only cables, structure with only membrane, and structure with both membrane and cables, which demonstrated major efficiency in the structure tested, to wind 170 km/h (minor displacements) that the structure tested to snow 50 kg/m, (less efficiency, major displacements). After the analysis the proposed structure's aerodynamic and load-bearing features would be helpful if building in an area frequented by high winds and in areas with little-to-no snow.

4 CONCLUSIONS

This methodology allows these conclusions:

- After doing the pertinent calculations, a tensegrity ring is proposed with a central dome, using diamond-shaped membrane patterns with twenty struts in a double layer, to cover a 40m diameter sports arena, which has a surface of 1.200m2 and can be occupied by approximately 626 people.
- Small changes in wind pressure or snow loads can have a major impact on the size and shape of the structural elements and the deformations that occur. Our initial testing demonstrated that it was necessary to re-optimize the structural elements to build a real-world structure.
- The uniqueness of these structures is that, even though they are auto-balanced for external loads such as wind and snow, it is sometimes necessary to increase the stiffness of their structural elements and/or reinforce them with external tubes and cables to prevent a collapse due to extraordinary conditions. To do so, we had to reinforce the membrane (Ferrari Fluotop T2 1302), the ring tubes (∅ 400-10_S235) and external tubes (∅ 250-8_S235).
- For the real-world structure that was tested with simulation software, the minor displacements observed during 170km/h wind was 200mm and the major displacements observed with 50 kg/m2 snow loads was 600mm. Therefore, due to the high displacements observed during snow loading and the small displacements observed during wind loading, the proposed structure's aerodynamic and load-bearing features would be helpful if building in an area frequented by high winds but would not be optimal for use in areas that experience heavy snow.
- This study is the first step in the process to construct a real-world building. To build the real-world structure, additional testing such as a dynamic analysis would need to be performed.

REFERENCES

[2] Sastre, R., *Disseny i Càlcul d'Estructures de Barres Totalment Articulades amb Grans Deformacions,* Ph.D. Thesis, Department of Architectural Technology I - UPC, Barcelona, 1981.

[3] Foster B., Mollaert M., *European Design Guide for Tensile Surface Structures*, Madrid: Munilla Lería, LD 2009.