XI International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2023
C. Lázaro, R.Rossi and R. Wüchner (Eds)

BEYOND BENDING: TENSION. MEMBRANE STRUCTURES II

JOSEP LLORENS

Barcelona School of Architecture (ETSAB), Universitat Politècnica de Catalunya
Diagonal, 649 - 08028 Barcelona, Spain
E-mail: ignasi.llorens@upc.edu

Key words: structural membranes, textile architecture, structural efficiency, optimization.

Summary. Jürgen Hennicke [1] challenged the designers of structural membranes stating that "*Structural membranes, if not designed as such, require an imposing steel structure*". Responding to this challenge, a comparative study has been launched to assess the impact on the design efficiency of considering or not the structural principles of membranes, that are: only tension, funicularity, curvature and pre-stress. In a previous paper (J.Llorens, 2023 [2]) the general approach of the research and the first results have been presented. This paper shows more cases to complete the most usual repertoire.

1 INTRODUCTION

Despite the fact that membrane structures have developed considerably due to their lightness and tolerance against deformations, they are sometimes designed without taking into account their basic principles, which are: only traction, funicularity, curvature and prestress. Because of this, instead of being sustainable structures, they end up being covered oversized steel structures.

2 COMPARATIVE STUDY

In order to quantify the impact of considering the structural characteristics of membranes in the design, a comparative study has being carried out. Starting from a case study consisting of arches supported by branched masts, alternative solutions have been examined including commonly used arrangements so that the transition from bending members to predominantly axial force members under tension or compression has been measured. The compared values have been the surfaces (covered floor area and membrane), their ratio, the weights (supporting structure and membrane). curvature (by the relation sag/span), maximal internal forces, total wind action (per square meter) and displacements. The analysis has been carried out using the programs RFEM and RWIND, considering a wind speed of 26 m/s in zone IV.

In a previous paper [2], I-beams, trusses, trussed arches, arches on branched masts, ETFE cushions, cable beams, flying masts, ridges and valleys and cable-domes have been considered. This paper deals with grid-shells, circular domes, inflatable tubes, textile halls, flying mast square modules, photovoltaic ETFE cushions, air supported structures and edge cable domes.

2.1 Grid shell

A common solution to implement ETFE cushions is the grid-shell, which has been popularized in widely disseminated works such as the Eden Project (Cornwall) [3] and the Cross Rail Station at Canary Wharf (London) [4], (figs.1 to 7).

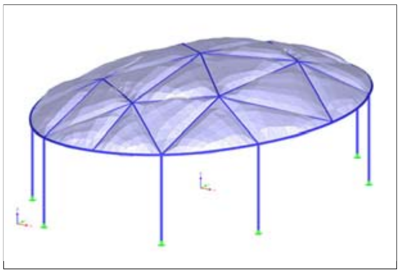


Figure 1: Isometric view

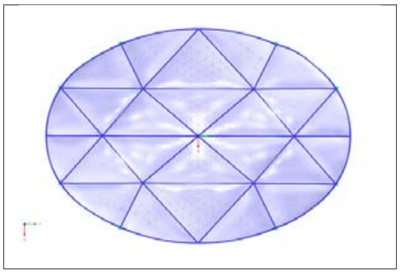


Figure 2: Plan

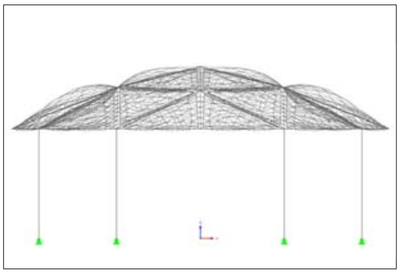


Figure 3: Elevation

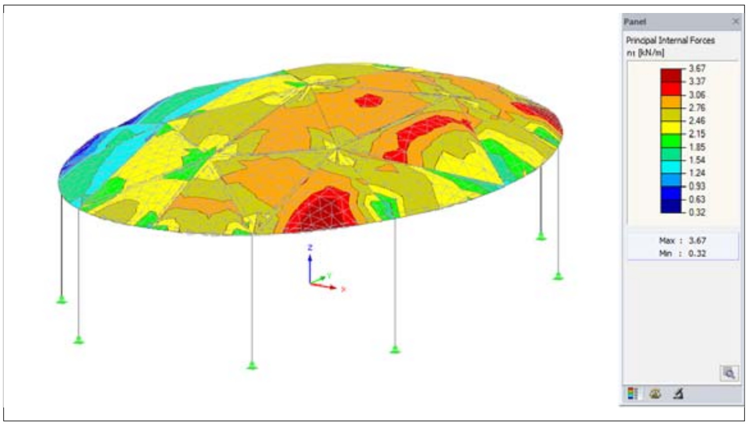
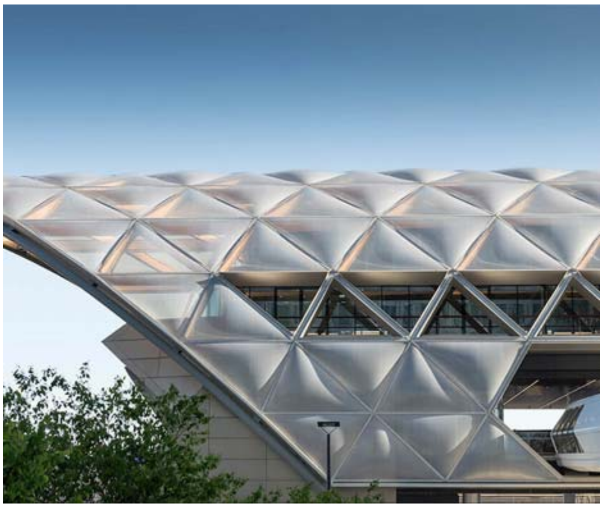


Figure 4: Internal forces

Length 34 x width 24; 642 m^2
Membrane surface: 1.417,18 m^2
Ratio: 2,21
Sag/span: 12,28%
Structure 13,54 kg/m^2
Membrane 1,10 kg/m^2
Total weight: 13,54 kg/m^2 -
Wind load: 312,25 N/m^2
Internal force: 3,67 kN/m
Deformation: 213,4 mm

Figure 5: Summary of results



Figures 6 and 7: Examples of application

2.2 Circular dome

The conventional solution for roofing circular areas is the dome. To materialize it with membranes, a radial skeleton of arches can be used (figures 8 to 12). It has been analyzed with and without ties to assess their influence (figs. 13 and 14). It has been found that the ties increase the deformation because they unload the perimeter ring. The other variables remain unchanged.

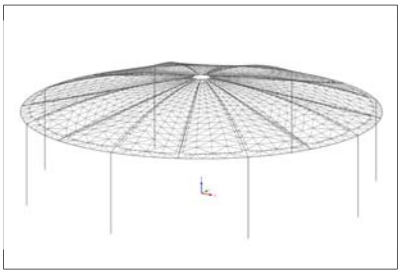


Figure 8: Isometric view

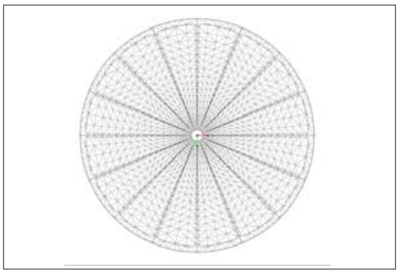


Figure 9: Plan

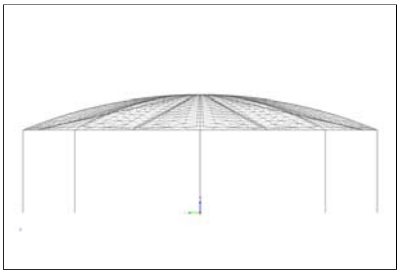


Figure 10: Elevation

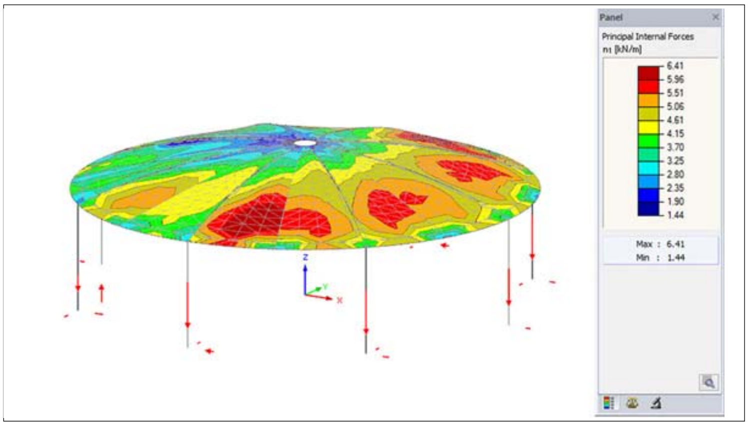
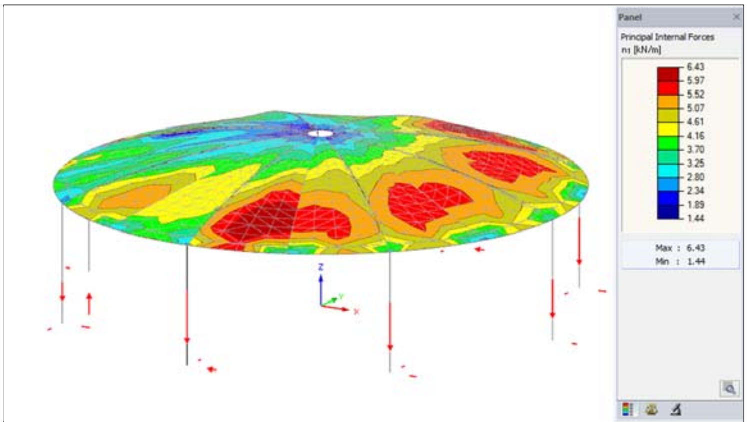


Figure 11: Internal forces (no ties)

Ø 30 m = 707 m^2
Membrane surface: 730 m^2
Ratio: 1,03
Sag/span: 2,13%
Structure 8,53 kg/m^2
Membrane 1,10 kg/m^2
Total weight: 9,63 kg/m^2 -
Wind load: 232,02 N/m^2
Internal force: 6,41 kN/m
Deformation: 147,2 mm

Figure 12: Summary of results



Ø 30 m = 707 m^2
Membrane surface: 730 m^2
Ratio: 1,03
Sag/span: 2,75%
Structure 8,76 kg/m^2
Membrane 1,10 kg/m^2
Total weight: 9,80 kg/m^2 -
Wind load: 232,07 N/m^2
Internal force: 6,43 kN/m
Deformation: 231,7 mm

Figure 13 (left): Internal forces (cable-stayed) - Figure 14 (right): Summary of results (cable-stayed)

2.3 Buildair hangar

Buildair hangars are air-inflated lightweight tubes where the bearing capacity is provided by air pressure blown inside. (figs. 15 to 21), [5]. Like air-supported structures, they do not use neither bending nor compression, because the load-bearing structure is pressurized air.

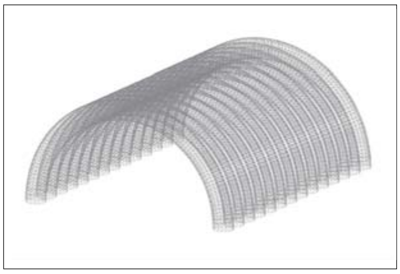


Figure 15: Isometric view

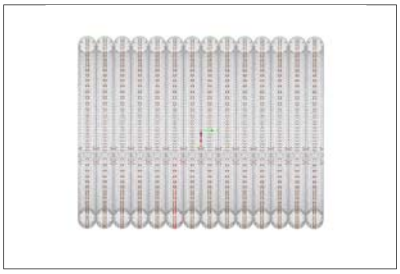


Figure 16: Plan

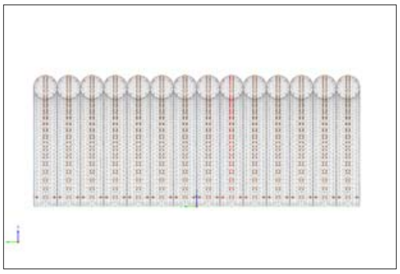


Figure 17: Elevation

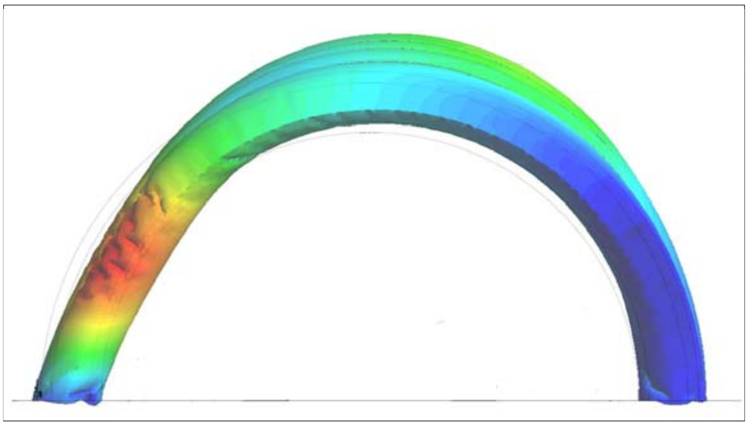


Figure 18: Transversal deformation (courtesy of Buildair)

37,8 x 30,4 m = 1.149,12 m^2
Membrane surface: 6.678 m^2
Ratio: 5,81
Sag/span: 50 %
Structure 0 kg/m^2
Membrane 3,94 kg/m^2
Total weight: 3,94 kg/m^2 -
Wind load:
Internal force: 30 kN/m
Deformation: 1230 mm

Figure 19: Summary of results

Figures 20 and 21: Examples of application

2.4 Textile hall

A widespread solution for temporary events is the textile hall. It is not considered theoretically to be a membrane structure but the cladding panels receive wind, rain and snow loads and interact with the supporting structure (figs. 22 to 28).

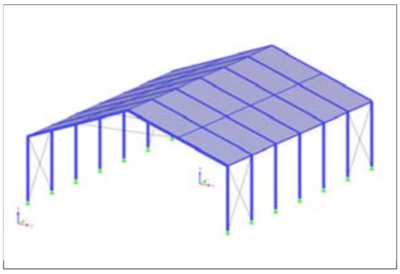


Figure 22: Isometric view

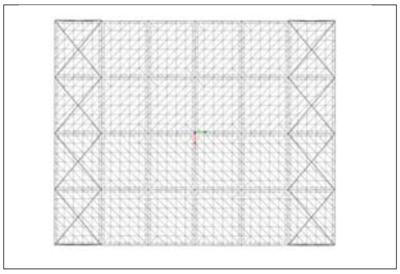


Figure 23: Plan

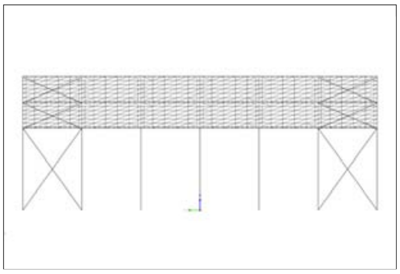


Figure 24: Elevation

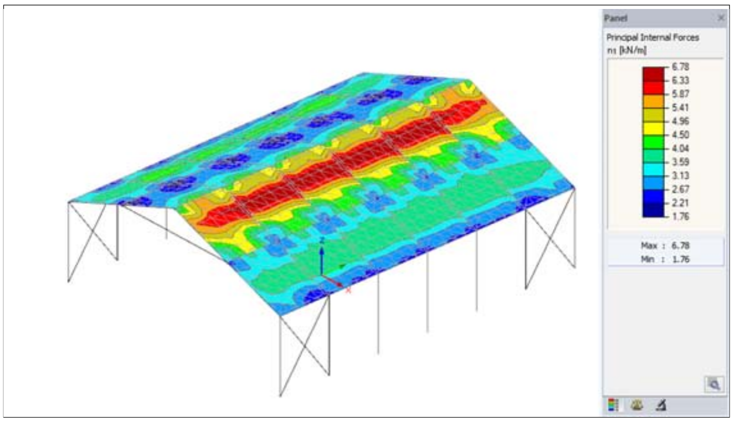


Figure 25: Internal forces

30 x 24 m = 720 m^2
Membrane surface: 766,43 m^2
Ratio: 1,06
Sag/span: 0 %
Structure 14,42 kg/m^2
Membrane 1,14 kg/m^2
Total weight: 15,56 kg/m^2 -
Wind load: 189,42 N/m^2
Internal force: 6,78 kN/m
Deformation: 208,8 mm

Figure 26: Summary of results

Figures 27 and 28: Examples of application

2.5 Flying mast square modules

A bending-free roof can be achieved repeating flying mast square modules. They were introduced with the Hajj Terminal of the Airport in Jeddah, 1982 and applied on a lower scale on the Office for Waste Management in Munich, 1999 (figs. 29 to 35).

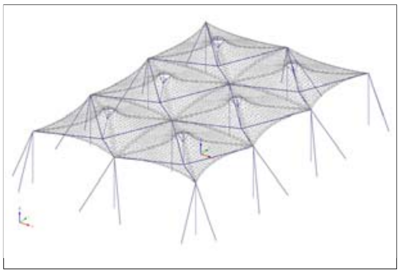


Figure 29: Isometric view

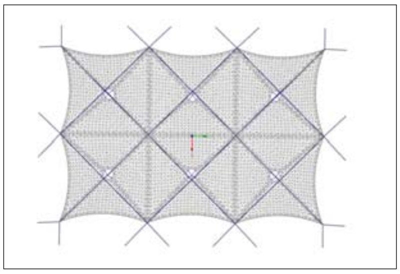


Figure 30: Plan

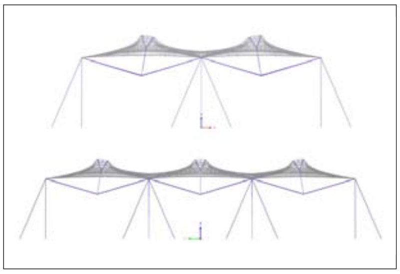


Figure 31: Elevations

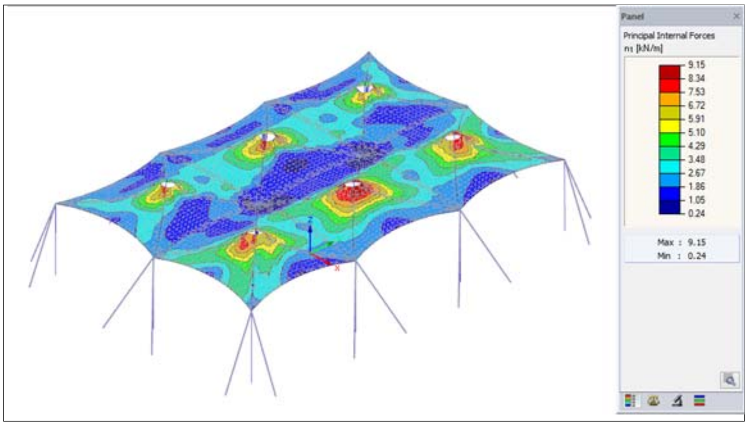


Figure 32: Internal forces

36 x 24 m = 864 m^2
Membrane surface: 786 m^2
Ratio: 0,91
Sag/span: 4%
Structure 3,84 kg/m^2
Membrane 0,97 kg/m^2
Total weight: 4,81 kg/m^2 -
Wind load: 92 N/m^2
Internal force: 9,15 kN/m
Deformation: 125,2 mm

Figure 33: Summary of results

Figure 34: Jeddah Airport [6]

Figure 35: Waste Management Office, Munich [7]

2.6 Photovoltaic ETFE cushions

An alternative to the previous solution, which relies heavily on bending is that of three-cord trussed girders and transverse arches supported by flying tetrahedrons that frame a series of ETFE cushions equipped with photovoltaic cells [8] (figs. 36 to 42).

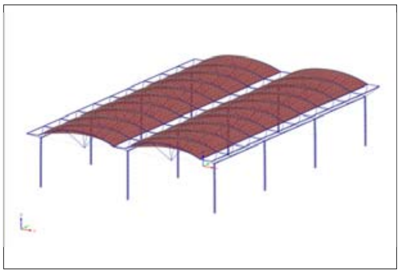


Figure 36: Isometric view

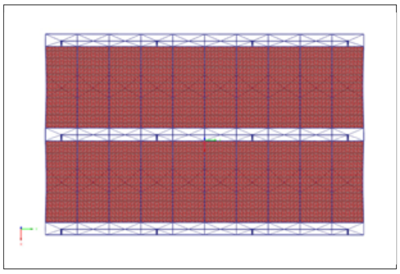


Figure 37: Plan

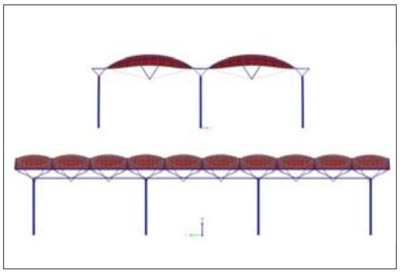


Figure 38: Elevations

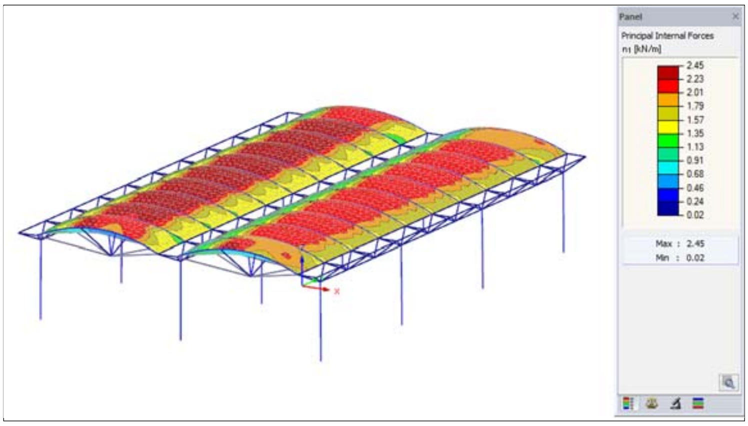
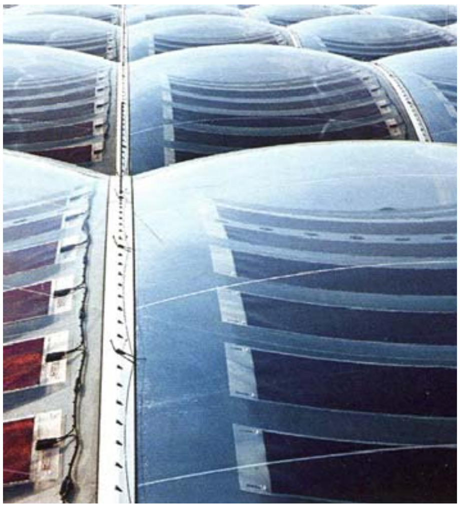


Figure 39: Internal forces

40 x 25,60 m = 1024 m^2
Membrane surface: 1789,58 m^2
Ratio: 1,75
Sag/span: 11 %
Structure 13,32 kg/m^2
Membrane 0,87 kg/m^2
Total weight: 14,90 kg/m^2 -
Wind load: 150,90 N/m^2
Internal force: 2,45 kN/m
Deformation: 34,3 mm

Figure 40: Summary of results



Figures 41, 42: Application of photovoltaic ETFE cushions, Munich [8]

2.7 Air supported structure

The air supported structure is the lightest solution. The drawbacks of internal pressure and total airtight enclosure can be solved by the air-inflated solution seen above. Deformations caused by the wind or snow can be reduced by over pressurising or guying (figs. 43 to 49).

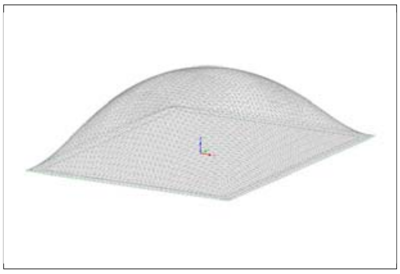


Figure 43: Isometric view

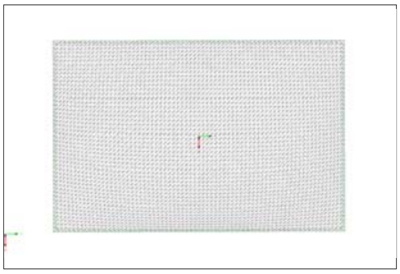


Figure 44: Plan

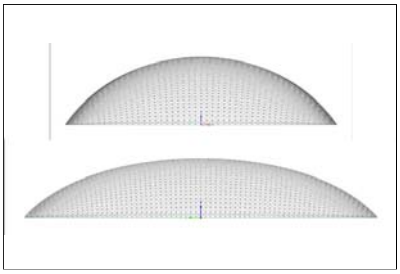


Figure 45: Elevations

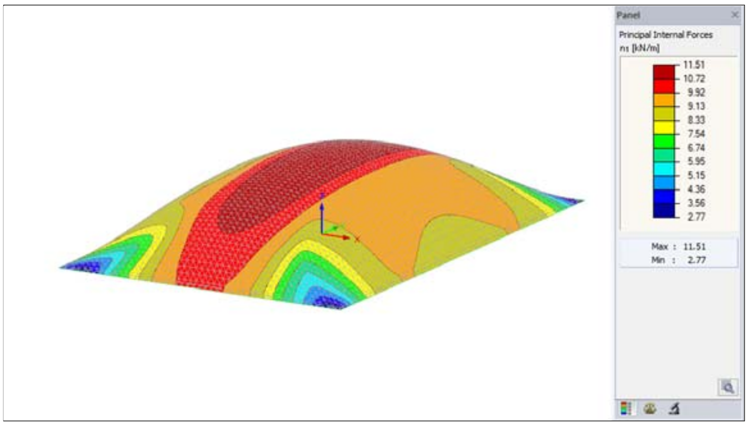


Figure 46: Internal forces

36 x 24 m = 864 m^2
Membrane surface: 991,07 m^2
Ratio: 1,15
Sag/span: 41,67 %
Structure 0 kg/m^2
Membrane 1,23 kg/m^2
Total weight: 1,23 kg/m^2 -
Wind load: 508,35 N/m^2
Internal force:11,51 kN/m
Deformation: 396,9 mm

Figure 47: Summary of results

Figures 48, 49: Examples of application

2.8 Edge cable dome

In the previous paper [2] a cable dome has been analyzed. It has not been in the group of the lightest solutions due to the compression ring. By replacing it with edge cables, the weight of the primary structure decreases from 9,49 kg/m^2 to 3,98 kg/m^2.

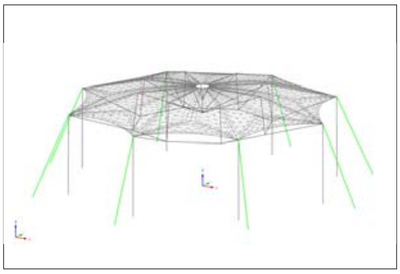


Figure 50: Isometric view

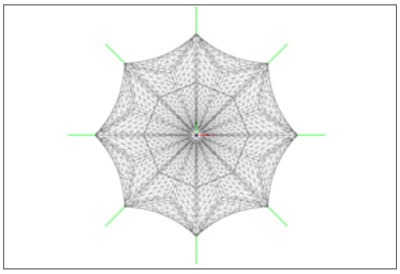


Figure 51: Plan

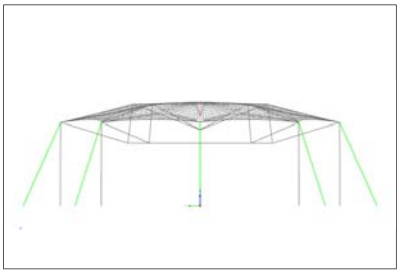


Figure 52: Elevation

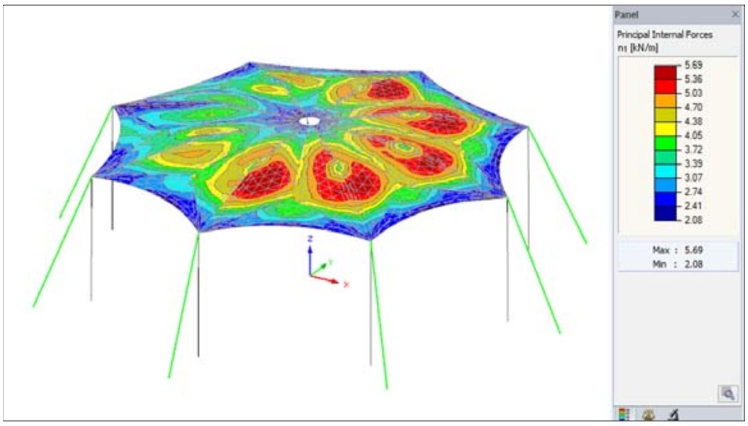


Figure 53: Internal forces

Ø 30 m = 707 m^2
Membrane surface: 578,6 m^2
Ratio: 0,82
Sag/span: 4,32 %
Structure 3,98 kg/m^2
Membrane 0,88 kg/m^2
Total weight: 4,86 kg/m^2 -
Wind load: 202,86 N/m^2
Internal force: 5,69 kN/m
Deformation: 363,1 mm

Figure 54: Summary of results

Figure 55: The circus tent saves on bending anchoring directly to the ground.

3 DISCUSSION

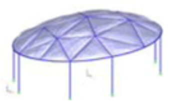
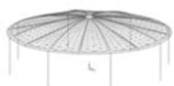
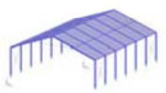
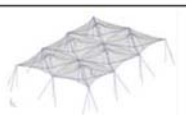
Case	Description	Areas (m^2)	**f/ℓ** (%) **Weight** (kp/m^2) **Wind** (N/m^2)	**Max. internal force and displacement** (kN/m and mm)
	GRID SHELL	Covered: 642	f/ℓ = 12,28%	Internal force: 3,67 kN/m
		Membrane: 1417,18	Weight 15,34 kp/m^2	
		Ratio: 2,21	Wind: 312,25 N/m^2	Displ. 213,4 mm
	CIRCULAR DOME	Covered: 707	f/ℓ = 2,13%	Internal force: 6,41 kN/m
		Membrane: 730	Weight 9,63 kp/m^2	
		Ratio: 1,03	Wind: 232,02 N/m^2	Displ. 147,2 mm
	TIED CIRCULAR DOME	Covered: 707	f/ℓ = 2,75%	Internal force: 6,43 kN/m
		Membrane: 730	Weight 9,80 kp/m^2	
		Ratio: 1,03	Wind: 232,07 N/m^2	Displ. 231,7 mm
	BUILDAIR HANGAR	Covered: 1149,12	f/ℓ = 50%	Internal force 30 kN/m
		Membrane: 6678	Weight: 3,94 kp/m^2	
		Ratio: 5,81	Wind:	Displ. 1230 mm
	TEXTILE HALL	Covered: 720	f/ℓ = 0%	Internal force: 6,78 kN/m
		Membrane: 766,43	Weight 15,56 kp/m^2	
		Ratio: 1,06	Wind: 189,42 N/m^2	Displ. 208,8 mm
	FLYING MAST MODULES	Covered: 864	f/ℓ = 4%	Internal force: 9,15 kN/m
		Membrane: 786	Weight 4,81 kp/m^2	
		Ratio: 0,91	Wind: 92 N/m^2	Displ. 125,2 mm
	PHOTOVOLT. ETFE CUSHIONS	Covered: 1024	f/ℓ = 11%	Internal force: 2,45 kN/m
		Membrane: 1789,58	Weight 14,90 kp/m^2	
		Ratio: 1,75	Wind: 150,90 N/m^2	Displ. 34,3 mm
	AIR SUPPORTED	Covered: 864	f/ℓ = 41,67 %	Internal force: 11,51 kN/m
		Membrane: 991,07	Weight: 1,23 kp/m^2	
		Ratio: 1,15	Wind: 508,35 N/m^2	Displ. 396,9 mm
	EDGE CABLE DOME	Covered: 707	f/ℓ = 4,32 %	Internal force: 5,69 kN/m
		Membrane: 578,6	Weight: 4,86 kp/m^2	
		Ratio: 0,82	Wind; 202,86 N/m^2	Displ. 363,1 mm

Table 1: Summary of results

This values show that the lightest structures are those that avoid or reduce bending: AIR SUPPORTED, BUILDAIR HANGAR, FLYING MAST SQUARE MODULES and EDGE CABLE DOME, even though they are more demanding in terms of internal force and displacement. The values obtained by varying the support structure range significantly from 0 to 14,42 kg/m^2 (figure 56). Observe also, excluding pressurized solutions, how the sag/span ratio affects the internal force (figure 57). The flying mast square modules do not follow the trend because they require considerable pre-stressing for stability.

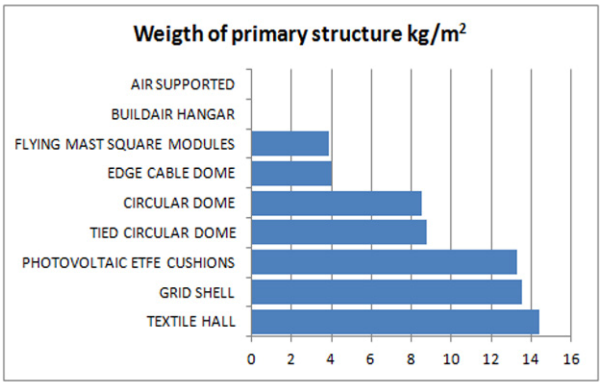


Figure 56: Weight of primary structure.

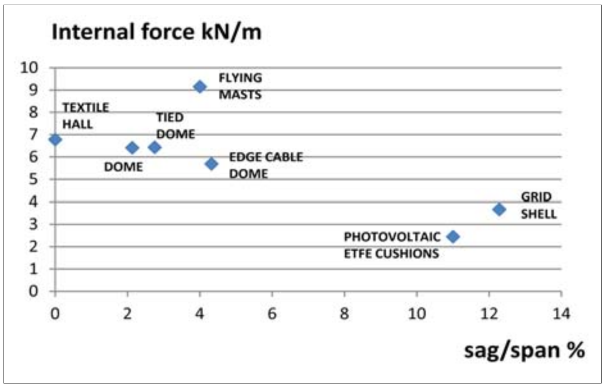


Figure 57: Internal forces versus sag/span.

The total wind action can be measured to assess how aerodynamic is the roof by adding up the reactions it mobilizes (figure 58). On the other hand, the ratios of surfaces and the weight of the membrane vary little (figure 58). Higher ratios correspond to multilayer roofs and lower ratios indicate that the entire floor plan is not covered due to the curved edges. Besides, attention has to be paid to the displacements that depend on spans, cantilevers and displacements.

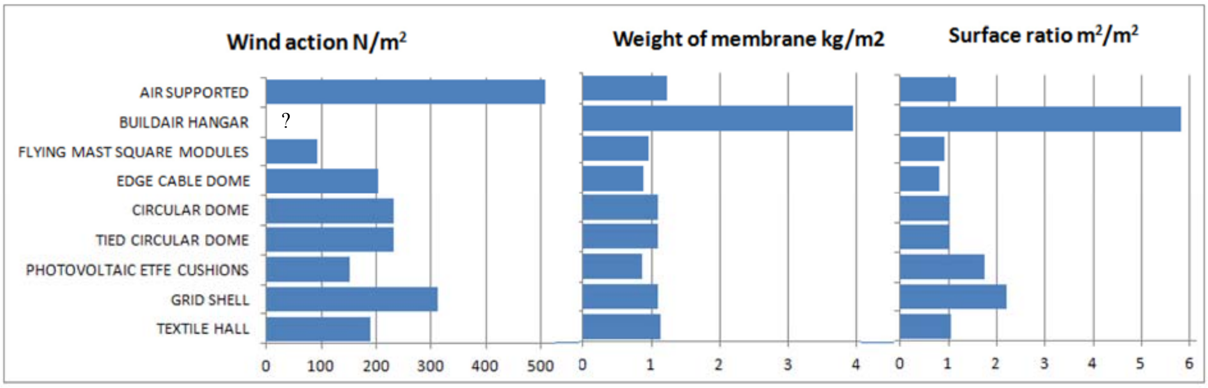


Figure 58

4 CONCLUSIONS

- The conclusions obtained during the previous research have been confirmed and completed.
- The lightest structures are those that avoid or reduce bending and the values obtained by varying the support structure vary significantly.

- The sag/span ratio affects the internal force.
- The ratios of surfaces and the weight of the membrane vary little.
- Attention has to be paid to deformations.
- In any case, what can really improve the efficiency of the structure is its conceptual approach. In the case of membrane structures, it is a matter of satisfying the basic principles of only tension, funicularity, curvature and pre-tension, avoiding bending.
- In addition, the methodology used and the values obtained can be applied to estimate and compare the efficiency of a design.

Acknowledgements

Structural and CFD analysis have been performed with RFEM and RWIND software available at: *https://www.dlubal.com/en/products/rfem-fea-software/what-is-rfem*
https://www.dlubal.com/en/products/stand-alone-structural-analysis-software/rwind-simulation

REFERENCES

[1] J.Hennicke, *The lightweight design approach*, Textile Roofs Workshop, Berlin, 2016.
[2] J.Llorens, *Beyond bending: tension, Membrane structures I*, TensiNet Symposium, Nantes, 2023.
[3] *Eden Project in St.Austell,* DETAIL 5, 2001, p.868-872.
[4] B.Scott & J.Rabagliati, *Case study. Crossrail Place, London E14, Foster and Partners,* AJ Specification, Feb. 2016, p.26-38
[5] J.Llorens, C.Estruch, J.Marcipar, J.M.González & E.Oñate, *Buildair H75-SAEI Hangar,* TensiNews 40, April 2021, p.10-12.
[6] H.Berger, *Light Structures - Structures of Light*, Birkhäuser, Basel 1996,
[7] *Office for Waste Management in Munich,* DETAIL 6/2000, p.1030-1035.
[8] *Canopy structure in Munich*, DETAIL 7-9/2013, p.773-777.