Proceedings of the International Association for
Shell and Spatial Structures (IASS) Symposium 2013
„BEYOND THE LIMITS OF MAN"
23-27 September, Wroclaw University of Technology, Poland
J.B. Obrębski and R. Tarczewski (eds.)

An integrated design of a free form space structure

Prof. Ing. Massimo Majowiecki [1], **Ing. Giovanni Berti** [2]

[1] Professor of Structural Architecture, IUAV University of Venice, Venice, Italy, *massimo.majowiecki@majowiecki.com*
[2] Structural Engineer, Studio Tecnico Majowiecki, Casalecchio di Reno, Italy, *giovanni.bertil@majowiecki.com*

Summary: In this paper is described the design of a large roof structure known as "Vela" built in Bologna in the 2012. This roof is a free form reticular space frame designed by integrating interdisciplinary performance evaluations such as the structural behaviour, the geometric regularity of the upper chord mesh and the thermal comfort depending by the sunlight exposure. Geometry is stressed as a key interface between the different properties.

Keywords: *Free form structure, reticular structures, integrated design, thermal comfort, structural analysis*

1. INTRODUCTION

In traditional design approaches, a given geometry is often expected to fulfill energy performance requirements mainly based on its material properties and technical construction systems. This leads to an inverse computing of the material properties that are needed in order to satisfy the expected performances. While such energy related inverse computing is commonly applied in an advanced stage of the design process, it is rarely used to address early design choices concerning the geometry of the project. The exploration of geometrical alternatives is a fundamental practice in design; driving this exploration based on performance evaluations is the nature of performative design. The concept of performative design refers to the generation of the shape as a process directly driven by the simulations of the related performances and on their evaluation based on a comparison between the intended and the analyzed performances. Feeding back the results of such evaluative process in the shape generation influences the design process toward performance improvements.

In line with this approach, this paper discusses a case study whose design process integrated performance evaluations at an early stage to explore geometrical alternatives of the project. The case study focuses on the "Vela roof," a large span roof in Bologna (Italy). Its design process used parametric modeling as a key support to explore performance oriented geometry [1].

Fig. 1 Rendering and photo of the "Vela" roof" in Bologna

2. DESCRIPTION OF THE "VELA" ROOF

The roof structure known as "Vela" was built in 2012 near the Unipol Tower in Bologna (Italy). The UNIPOL Project consists of an intervention on a 45.000 sqm plot located between a city by-pass and a suburban area. The architectural process was led by Open Project Office and the structural design by Studio Tecnico Majowiecki. Spanning in scale from the urban level to the detailed design, the project includes three building blocks enclosing a system of urban spaces. These latter are partially covered by the Vela roof. This is a large span structure of approximately 65x65 meters, offering a multilevel sheltered area faced by shops, services and offices. With the help of an interdisciplinary team of Delft University of Technology [1] the large span roof has been designed by integrating interdisciplinary performance evaluations such as the structural behaviour, the geometric regularity of the upper chord mesh and the thermal comfort depending by the sunlight exposure.

2.1. Structural system

The structure is a double-layered space frame with an external triangular-based layer and an internal rectangular-based layer. These layers has been shifted and oriented in order to align the position of diagonal bars with the lower chord bars: this structural layout produces a good architectural look and allows to remove the not necessary lower chord nodes, with an aesthetic and economic advantage.

This geometry is the result of an investigation made among various kind of upper chord tasselation in order to find the better solution in terms of architectural look and structural efficiency, some of these tasseletions schemes are shown in . The geometry f the roof is important to avoid problems with the water ponding and so was also made and investigation about the local inclination fo the upper chord surface in order to ensure a good water outflow.

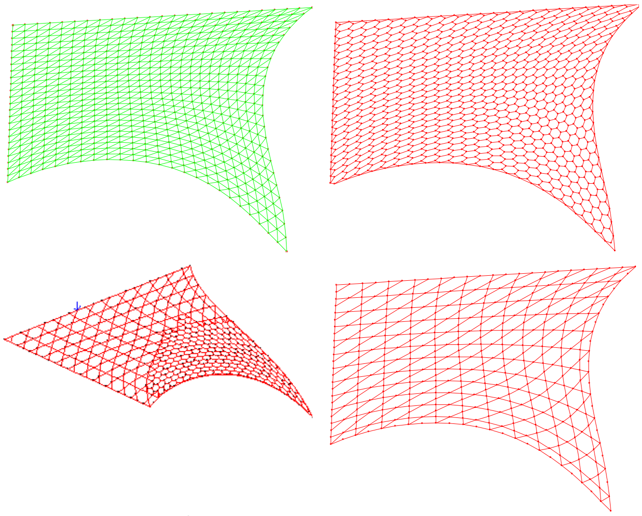

Fig. 2 Various kind of upper chord tasselation that have been investigated

The elements of the top chord layer have rectangular hollow cross sections and are connected with rigid nodes: these characteristics allow to apply loads directly on the upper chord elements without the use of purlins with both economichal and aesthetic advanteges. The lower chord elements are realized with circular hollow cross sections and connected with spherical nodes (Fig. 3).

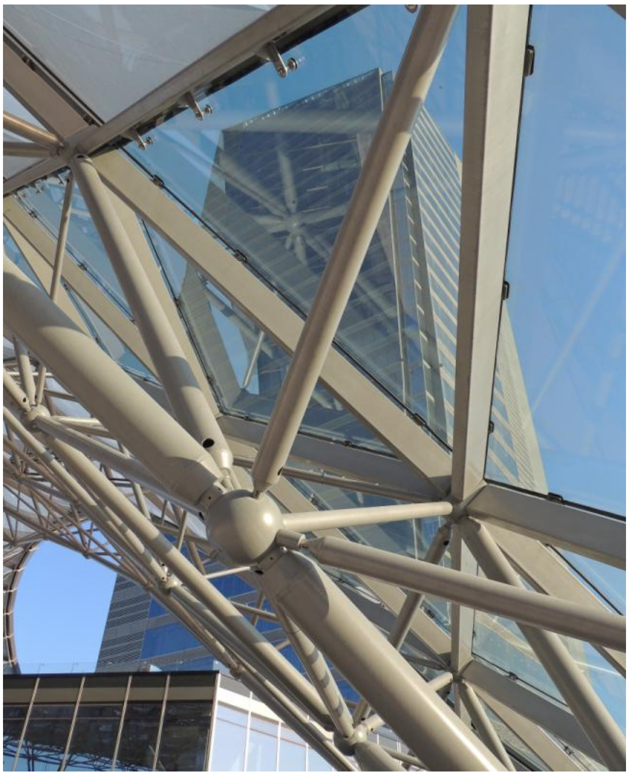

Fig. 3 Upper and lower chord nodes and bars of Vela roof in Bologna

The roof structure is anchored to the buildings in three points, as shown in the Fig. 4. The node n° 8 is restrained to the movement in z and y direction. At the end of the construction of the roof the node n°8 has been left free to move in the x direction under the action of the structural self weight of the structure. Once the structure has settled under the load of its own weight the node 8 was also restrained to the translation in the x direction. This procedure was performed in order to obtain a arch behavior in the longitudinal direction of the structure once it is subjected to accidental loads and simultaneously avoid that under the action of its own weight the constraints are constantly subject to an horizontal force.

The nodes 6 and 7 are instead constrained only to the vertical translation: this type of constraint was necessary since these bearings are located on the top of different buildings and so they can have different movement in case of seismic action (**Fig. 4**).

The nodes n° 2 and 4 are constrained in x, y and z directions and so they give a fix constrain to the roof structure.

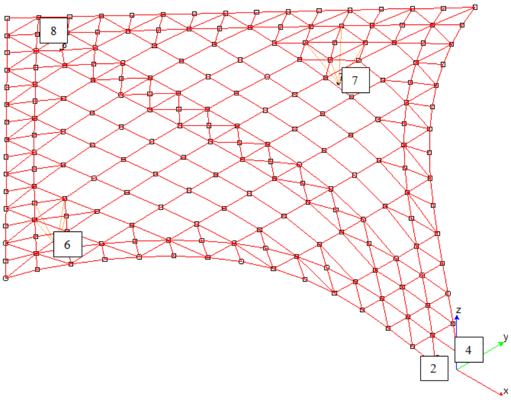

Fig. 4 Anchor points of the roof structure

a) b)

Fig. 5 Connection ofthe mobile nodes n° 6 and 7: a) Sliding devices and anchor of the ropes, b) Connection of the ropes with a node of the lower chord of the roof structure

On the steel part of the reticular structure have been performed tests of mechanical strength and analysis to determine the chemical composition of the material. Mechanical resistance tests have been performed also on some nodes of the structures as shown in Fig. 6.

Fig. 6 Resistance test of a node performed on a laboratory

2.2. Cladding system

Since the spaces enclosed by the Vela are supposed to buffer between indoor and outdoor, the demands for the thermal comfort are less strict than what is expected for fully indoor spaces. The main task can be summarized in a simplified approach that aims at mitigating the worst thermal conditions, avoiding uncomfortable conditions of summer overheating and mitigating cold winter conditions and uncomfortable daylight. Referring to passive strategies, passive cooling for summer time and passive solar heating for winter conditions are therefore both considered, which together will contribute in achieving the thermal comfort with a lower need for imported energies. The analysis of the local climate conditions allows identifying the relative potentials and contributions of both. As shown by the EERE (2009) statistics data, the local climate in Bologna is characterized by high annual thermal variation of about a 22°C difference between the coldest month, January, and the warmest, July; limited wind speed and absence of a dominant wind direction; high air humidity and little precipitations. In such a condition, possible summer overheating under the roof was identified as the most critical risk: this requires a cladding system with low total solar energy transmittance factor (g-value). At the same time, under the roof, daylight should be guaranteed with a daylight factor sufficient also for the indoor spaces facing the covered square: this requires a cladding system with high daylight transmittance (Fig. 7).

These requirements are asked based on the properties of the materials and on the geometrical design of a north-south shading system.

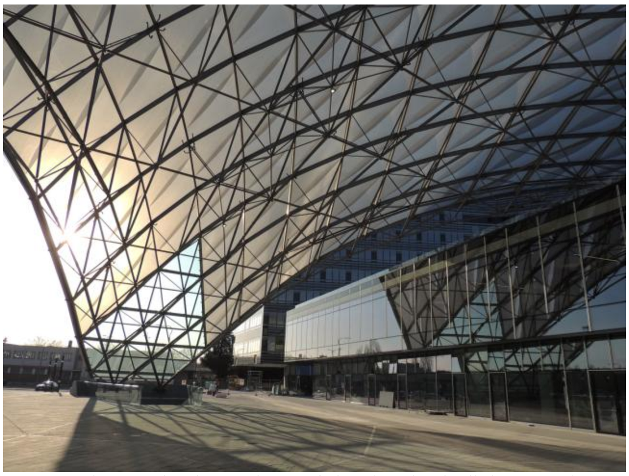

Fig. 7 A photo under the “Vela” roof showing the daylight transmittance of the ETFE panels

2.2.1. Geometrical configuration and material properties

ETFE modules are made of 2 layers, a top one and a bottom one. Each layer of each cushion consists of two parts: one opaque (printed) and one transparent (without printing). For each cushion, the location of the opaque and transparent parts of the layers is determined based on the orientation of the cushion with respect to the North-South axis: the top layer is printed in its south facing part while the bottom layer is printed in its north-facing part. The extension of the opaque and transparent parts of the layers is determined based on an opening angle of 70 degrees (Fig. 8).

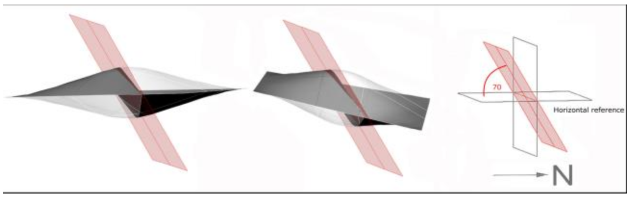

Fig. 8 3D views of ETFE cushions with North-South shading printing on top and bottom layers: horizontal position and tilted position; external horizontal reference and plane determining the opening angle.

The system is meant to block the direct solar radiation while it allows the transmission of diffuse daylight. In such a system, the ratio r between the span and the height of each cushion directly affects the daylight performances of the cladding since the higher the ratio, the better the system performs: concerning this aspect, a value between r = 0.23 and r = 0.28 is required. When the ratio gets close to 0.23, an opening angle of 60 degrees can also be used in order to compensate the lost in daylight; since this would increase the g-value of the system, the opacity of the printed part can be increased. In any case, the recommendation is a combination of ratio, opacity and opening angle which reduces the g-value and increases the indirect daylight transmittance.

Concerning daylight, in order to provide a high transmission of indirect solar light, the daylight transmittance of the transparent parts of the top and bottom layers is asked as high as possible, with a minimum of 85%.

Concerning thermal performances, in order to obtain an acceptably low g-value of the cladding system, both the direct and indirect transmittance of the system needs to be small. In order to reduce the direct transmittance, the average solar energy transmittance of the printed parts is asked with a maximum value of 30%; in order to reduce the indirect solar energy transmittance, opaque parts should have a low average absorbance factor of approximately 0.20, especially with respect to the bottom printed layer. This results in an average external reflectance of at least 45%.

2.2.2. Summary of requirements regarding thermal comfort

According to the analysis carried out the Vela roof has to satisfy the following requirements regarding thermal comfort and day lighting:

- the roof should have an average light transmittance LTA of 30%
- the roof should have an average g-value of 30%
- the roof should have an indirect solar transmittance of 5%
- roof openings are advised around 20 m2 in middle zone
- additional use of adiabatic cooling is recommended (the minimum evaporation capacity required is of 750 liter per hour)

3. PERFORMANCE ORIENTED PARAMETRIC DESIGN OF THE CLADDING SYSTEM

The geometry of the roof proves to have a large impact especially on the control of the airflow for cooling and on the reduction of solar gain. In order to explore geometrical design alternatives, parametric modeling was used. Parametric modeling allows representing both geometrical entities and their relationships, which are structured in a hierarchical chain of dependencies established during the preliminary parameterization process. The independent properties of the model are usually expressed through independent parameters, and their variations generate different configurations of the model. By making use of this potential, three project scales were parametrically explored. At the large scale, parametric variations of the overall shape of the roof were investigated in relation to cooling through ventilation and here the parametric model allowed for the generation of different configurations of the roof, including its structural morphology and variations of its structural tessellation. At the medium scale, the integration of openable modules was investigated in relation to air extraction for cooling; with respect to this, the parametric model allows exploring openings based on variations of size and distribution. Although variations in the geometry of the roof and the integration of large openable systems have not been integrated in the final design, the support provided by parametric modeling demonstrated great potentials in investigating both the large and medium scale of the project [2].

3.1. Parametric geometry

The parametric study first focused on a generic single ETFE pneumatic module. This was modeled by taking into account three main aspects: its direct relation with the structural geometry, its orientation with respect to the cardinal directions and the geometrical key factors affecting the transmission of the solar energy.

Focusing on the first aspect, the geometry of the cladding module and the structural geometry of the roof are reciprocally constrained. A double layer space frame was previously chosen as the typology of the structural system based on architectural and structural evaluations. In order to match the ETFE modules with the tessellation of the top layer of the space frame, the parametric ETFE module has been built based on a polygonal frame that acts as an interface between the cushion and the structure.

This structural geometry was parameterized and modeled based on UV coordinates and the scripts were customized in order to meet the diagonal orientation of the pattern. The problem is reduced to a two dimensional array set on Pythagoras relationships (Fig. 9), the number of rows was defined as an independent parameter, *n*, to regulate the density of the grid.

Such a polygonal interface can be built in order to fit different possible structural tessellations allowing applications to different structures. Its potential is great, especially in combination with parametric models of the structure that support the explorations of different structural tessellations. This requires generalizations of the geometry of the cladding modules, but provides advantages in quickly enlarging the solution space of the parametric model.

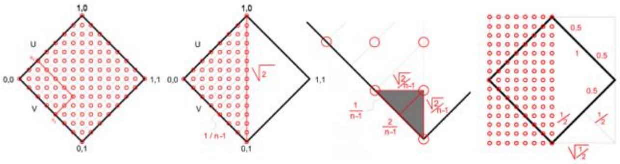

Fig. 9 Parameterization of the diagonally oriented grid of point based on UV coordinates

A quadrangular polygon built by vertices was used as the highest entity in the dependency chain of the ETFE module. Based on this polygon, NURBS surfaces were built to describe the inflated top and bottom ETFE layers.

Focusing on the second aspect, the printed shading parts on the so obtained ETFE layers were modeled by taking into account their North-South orientation. This implied the assumption of an absolute reference that remains constant for whatever shape and orientation of the modules. An external reference, to which the module has been constrained but that remains independent of the geometry of the roof in order to maintain its consistency even in case of rotations and variations of the roof structure, fulfills this requirement. This can be seen as a potential also when applying the modules to different structures.

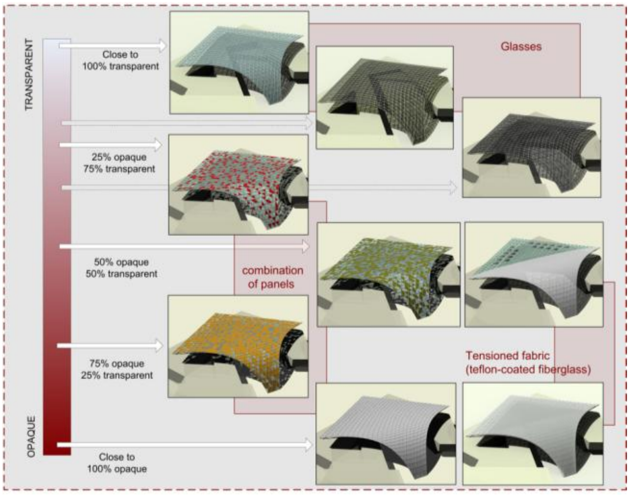

Fig. 10 Different types of cladding system

Focusing on the third aspect, different variations of the module were investigated for the solar energy transmission of the system and expressed through independent parameters which act as variables meaningful for the energy transmission (Fig. 10). Among many variables, the most meaningful seemed to be the opening angle between the top and bottom printing. While the printed part of the top layer is constrained to face the South and the printed part of the bottom layer to face the North, the opening angle is the angle of rotation of the top and bottom printed parts around the East-West axis. The variations of such angle affect both the income of direct solar radiation and the daylight transmission, where increasing the angle decreases both. A second meaningful variable was identified in the height distance between the top and bottom layers, in their farthest points. This geometrical property affects the amount of incoming indirect daylight. However, structural reasons constrained the proportion between the height and the polygonal base of the cushion. This implied a proportion with respect to the short side of the polygonal frame, with a ratio of 0.24.

The resulting module was then saved as a replicable feature; in this way, the module could be propagated onto the structural geometry by guaranteeing the relationships with the structural geometry as well as with the North-South direction.

3.2. Performance evaluations

The final parametric model allowed the generation of the cladding alternatives based on different opening angles. The obtained geometrical alternatives were evaluated based on their performances, with a combination of manual and software simulated calculations, in reciprocal crossed validation, as exemplified in the following figures and tables.

Table 1 Average monthly g-value (%) for different opening angles

	Opening angle 40°	Opening angle 50°	Opening angle 60°	Opening angle 70°
Jan	26	24	23	22
Feb	28	27	25	24
Mar	32	30	28	27
Apr	35	32	30	29
May	38	34	32	30
Jun	39	35	33	30
Jul	39	35	32	30
Aug	37	33	31	29
Sep	34	31	29	28
Oct	30	28	27	26
Nov	27	26	24	23
Dec	25	23	22	21

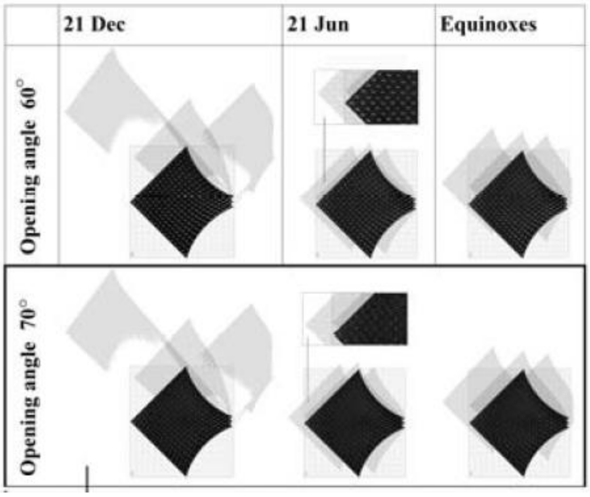

Fig. 11 Shadow simulation

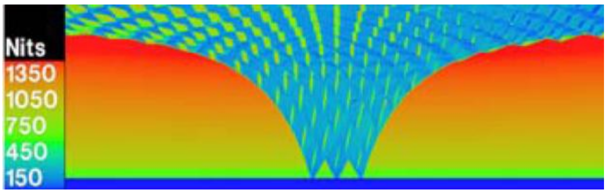

Fig. 12 Daylight simulation

Table 2 Diffuse light transmittance factor; g-value; ratio; average physical equivalent temperature (July)

	LTA %	g-value %	LTA/g	Average PET C°
Opening	32	33	0.97	34

angle 60°				
Opening angle 70°	30	30	1.00	33.5

Fig. 11 and Fig. 12 show the key steps of the process by illustrating some analyses concerning ETFE modules having different opening angles. Specifically, for a transmittance and an absorbance of the printed parts of 30% and 15% respectively, the images show: Table 1 some results of the investigations on the g-value calculated for opening angles between 40 and 70 degrees, during the year; Fig. 11 the shadows (and direct solar exposure) simulated in Autodesk Ecotect 2009 on parametric instances for opening angles between 60 and 90 degrees, during the year; Fig. 12 the results of a daylight simulation on a parametric instance for 70 degrees, done in Radiance to investigate the daylight factor (resulting of 35%, reduced to 26% by including the roof structure) and daylight levels and distribution; Table 2 the final comparison between the g-value and the daylight transmittance and calculation of the physical equivalent temperature to assess the summer thermal comfort, for opening angles of 60 and 70 degrees.

The best balance between a low solar factor and a high daylight transmission was identified to correspond to an opening angle of 60 to 70 degrees (Fig. 13).

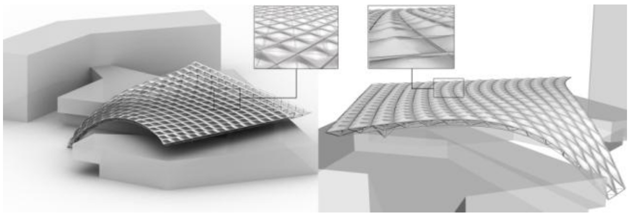

Fig. 13 Parametric instance of ETFE cladding, for an opening angle of 70 degrees

4. CONCLUSIONS

Throughout the overall design process, the role of the geometry with respect to solar energy performances revealed a high relevance and the use of parametric modeling in supporting the exploration of design alternatives showed high potential. A first key advantage is the automatic generation of geometrical variations, which provides large sets of alternative design solutions. Three aspects of this potential are highlighted here; the first one relates to the importance of visualizing the alternatives; the second one to the emergence of un-conceived geometrical configurations; the third one to the availability of geometrical instances to be analyzed based on simulation software and performance evaluation processes. Each of these aspects does not directly allow a quicker convergence toward suitable solutions, but is meant to increase the potentials for a higher quality of the design. When looking at traditional processes, in fact, time restrictions and other limitations make designers commonly consider only small subsets of the possible design candidates and most design processes explore a relatively narrow range of possibilities (Josephson, 1997). Based on the automatic generation of geometrical variations, the potentials of parametric design have been discussed in direct contrast to this limit. It is also important to recall that such generation effectively supports the process only when the generation includes meaningful design solutions (which mainly depends on the parameterization process), and is properly explored (by searching for solutions that satisfy the given specifications). In this respect, the early interdisciplinary collaborations that are necessary in order to parameterize the geometry as well as select the design alternatives for deeper evaluation must be mentioned as having a positive influence. Finally, based on the described case study, it can be concluded that a larger and earlier integration of parametric techniques in the design process is highly recommendable in order to further make use of their potential, especially when such techniques are more closely combined with performance simulation software and computational search techniques.

5. REFERENCES

[1] Turrin, M., Stouffs, R., Sariyildiz, S., 2010b, Parametric design of the Vela roof. A case study on performance oriented exploration of design alternatives. In: *Proceedings of ASCAAD 2010*, Fez, Morocco, 19-21 October 2010.

[2] Turrin M., von Buelow, P., Stouffs, R., Kilian A., 2010d, Performance-oriented design of large passive solar roofs. A method for the integration of parametric modeling and genetic algorithms. In: *Proceedings of eCAADe 2010, 28th Conference: Future Cities*, Zurich, Switzerland, 15-18 September 2010, pp. 321-330.

[3]