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

BETWEEN STRUCTURE AND ARCHITECTURE

N. BALDASSINI[*], O. GUIDET[*] AND K. DE RYCKE[*†]

[*] Bollinger+Grohmann (B+G)
15 rue Eugène Varlin 75010 Paris, France
e-mail: nbaldassini@bollinger-grohmann.fr
oguidet@bollinger-grohmann.fr
kderycke@bollinger-grohmann.fr
web page: https://www.bollinger-grohmann.com/

[†] Ecole nationale supérieure d'architecture Versailles (ENSAV),78000 Versailles, France
The Bartlett School of Architecture, UCL, London, UK

Key words: Tensile structures, Membranes, Large span facades, R&D.

Summary. Thanks to their flexibility, lightness and robustness, textile works are often used to cover large spaces. Structural efficiency of tensile structures can usually be related to a double curvature geometry. However, the project of the new Brugge Stadium offers a new challenge: the realisation of a flat façade with porous zebra strips of different porosity. The strips are 45° inclined with alternating porosities to create visual zebra effect during day and night as it permits light to pass from both the inside and the outside. With this choice come several design issues. The porous meshes should be prestressed, with its uncommon angle of 45° oriented mesh and the structural span is too important for existing meshes. Consequently, a close collaboration with textile companies was necessary to develop a mesh tailored on the need of the project and on the architectural design intents. The design process followed several steps, among the most significant : 1) understanding of the structural challenges to develop a new product adapted to the project 2) definition of the design criteria related to the dynamic behaviour of flat facades, 3) comparison of a stiff and a soft supporting structure (straight cables) 3) interface of the façade to the main concrete structure of the stadium. In the final design, the membrane is supported by a steel structure diagonally arranged to follow the pattern of the membrane arranged in 35-metre long strips. The steel beams inclined by 45° are preferred to the cable solution: the complications due to pretension are limited, the connection details can be designed to merge visually with the strips, the forces applied to the concrete structure are limited. A special mesh was developed to guaranty the 45% porosity required by the architect and the structural requirement for a 6m span diagonal strip : this design process hints at future design possibilities for textiles structures that could match the architectural intents with some R&D and a direct collaboration with the textile industries.

1 INTRODUCTION

Most tensile structures take advantage of their 3D geometrical shape to balance tension forces, ensure a good and optimized mechanical behaviour and remain stable against external loads. But in the absence of curvature, the structural efficiency of flat tensile facades needs to be studied more carefully, as the pretension needs to be a lot higher to ensure the mechanical behaviour of the membrane. This high level of pretension leads inevitably to other challenges, especially concerning the façade structural frame and the connection details.

This paper relates the study around the challenging façade of the new Club Brugge Stadium, designed by the architects SCAU and B2Ai for the city of Bruges in Belgium. This project is currently under design phase after winning the competition in 2020, and features flat tensile facades, with porous zebra strips of different porosity. A continuous vertical screen that wraps the perimeter predominantly composes the stadium envelope, spanning vertically from level 1 to the edge of the roof. The envelope offers protection to the external space that is sheltered underneath the stands: visual protection and functions as a rainscreen. Thanks to its perforation and semi-transparency, it also permits light to pass from both the inside and the outside, enhancing the effect of illumination. The membrane has an inclined layout and is organised in strips of alternating porosity. To match the inclination of the strips of alternating porosity and ensure their manufacture, the warp and weft direction of the membrane are also inclined at 45°. The screen’s height varies between 17.5m and 24.5m depending on the façade and is supported by regularly spaced concrete columns that supports the steel roof. Columns are spaced every 8.2m to 8.6m.

Fig. 1 : Design intent for the porous zebra façade (cc SCAU)

North facade : columns spaced 8.2m, façade's height 24.5m

West facade: columns spaced 8.6m, façade's height 23m

South facade : columns spaced 8.2m, façade's height 24.5m

East facade : columns spaced 8.2m, façade's height 17.5m

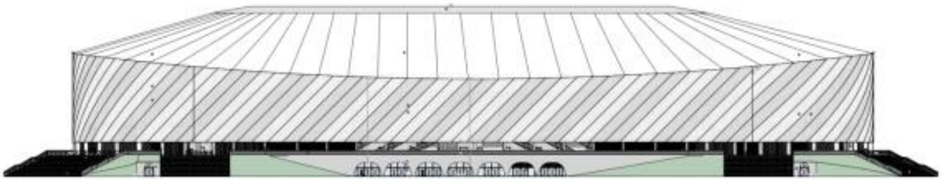


Fig. 2 : Club Brugge Stadium Elevation

The remainder of this paper is organized as follows: Section 2 describes the structural challenges encountered during the study of the initial design (high pretension, detailing, dynamic behaviour…). Section 3 describes the final design, as well as the collaboration with the textile manufacturer and the result of R&D on this project to attain the challenging architectural intents.

2 INITIAL DESIGN AND STRUCTURAL CHALLENGES

Flat façade panels of large dimensions are nowadays rather common and ordinary and can easily reach a 6m span. For Brugge Stadium, the flat panels are defined by the spacing of the columns and reach a span of at least 8m, and a height of 24m. This challenge also presented some extra technical constraints as the panels were supposed to be composed of porous fabric (which has poor resistance) oriented at 45° and with welded seams joining stripes with different porosities.

The design tried to deal with these parameters explained in the following paragraphs, and find an equilibrium between the necessary high pretension, the static and dynamic behavior of the porous fabric and the detailing.

2.1 Flat facades and high pretension

Flat panels need high prestress forces to stiffen the fabric with respect to orthogonal (wind) loads. Excessive deformation leads to uncontrolled dynamic behaviour and should be avoided, hence a limited deflection (detailed in section 2.2). As an example, the theoretical necessary prestress was 8kN/ml to respect all the deflection criteria.

However, the resistance of the fabric already limits the applicable prestress. Meshes with a porosity of 22% and 45% are Type II fabrics, with poor resistance performance (around 80 kN/ml in weft direction), whereas Type IV fabrics are usually used for flat panels (resistance around 130 kN/ml in weft direction). Additionally, “the art-rules” and the contractors highly recommend not to work with a prestress higher than 2.5 kN/ml, with a maximum of 5 kN/ml. A higher pretension is harder to obtain on site due to the compensation that needs to be considered during installation.

2.2 Deflection criteria: static displacement and dynamic behaviour

Static displacement criteria are important for the serviceability of the structure and to ensure that the fabric does not touch any fixed or sharp element while deflecting. However, the deflection regime and the out of plane stiffness give a preliminary indication of the dynamic behaviour.

To evaluate the behaviour under static displacement, one can try to relates to the usual geometric rule *chord/deflection<20* used for curved membranes. That sets an indicative maximal deflection of L/20. According to the fluttering criteria of the European Design Guide of Tensile Surface Structures, it is also possible to evaluate the stiffness of a tensile structure (cf Fig 2.). Even if this criterion regrettably complies more with double curvature design and is not applicable for flat surfaces since deflections are significantly larger and stiffness much lower, it is still a first indication of potential dangerous dynamic behaviour if ever the stiffness is below 0.1kN/m².

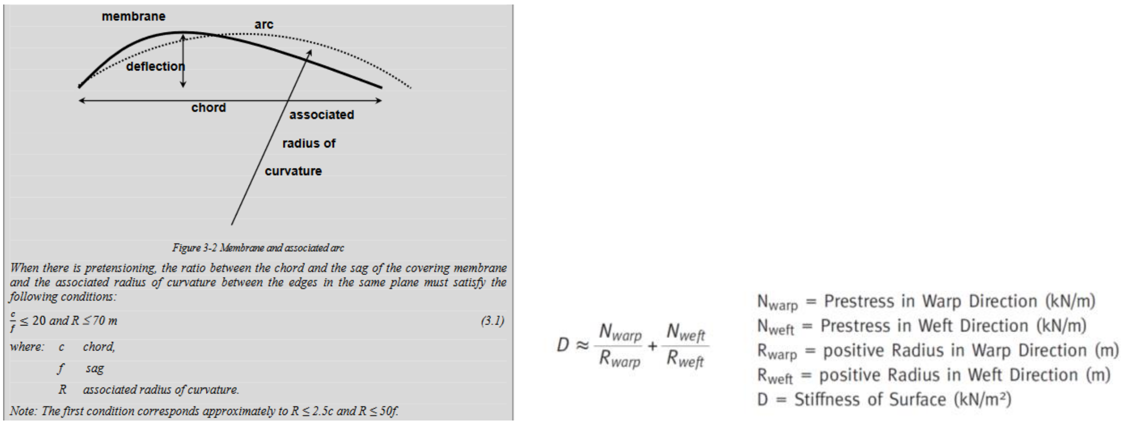


Figure 3-2 Membrane and associated arc

When there is pretensioning, the ratio between the chord and the sag of the covering membrane and the associated radius of curvature between the edges in the same plane must satisfy the following conditions:

$$\frac{c}{f} \leq 20 \text{ and } R \leq 70\ m \qquad (3.1)$$

where: c *chord,*
f *sag*
R *associated radius of curvature.*

Note: The first condition corresponds approximately to $R \leq 2.5c$ *and* $R \leq 50f$.

$$D \approx \frac{N_{warp}}{R_{warp}} + \frac{N_{weft}}{R_{weft}}$$

N_{warp} = Prestress in Warp Direction (kN/m)
N_{weft} = Prestress in Weft Direction (kN/m)
R_{warp} = positive Radius in Warp Direction (m)
R_{weft} = positive Radius in Weft Direction (m)
D = Stiffness of Surface (kN/m²)

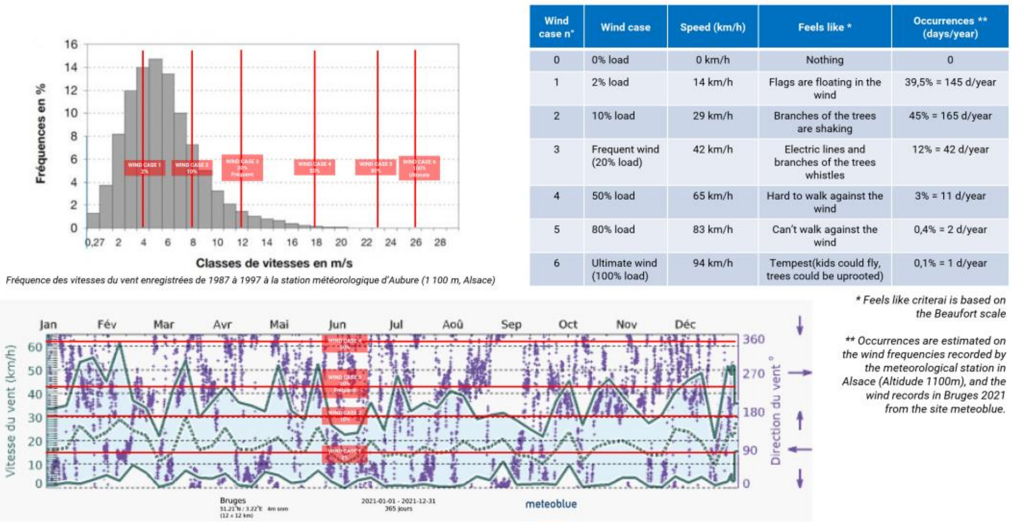
Fig. 3: Extract of the Guideline for a European Structural Design of Tensile Membrane Structures Made from Fabrics and Foils

The biggest risk of flexible structures is flutter under dynamic behaviour. This phenomenon is not applicable here since, to activate it, it is necessary to have airflow on both sides of the surface. In our case: the façade encloses an interior space, and the porosity balances the pressure without developing any dynamic airflow.

On the other hand, literature, and university reports that for particularly flexible membrane a wind study is required. Despite actively researching further information about this type of calculation, we discovered that there is a mismatch from what is prescribed and the state of the art. We found no previous dynamic study nor any methodological indication.

Based on this absence of information, we addressed a wind tunnel test specialist, to commission experimental wind studies to confirm the dynamic behaviour. Both Wacker and RWDI had not performed this type of test before but agreed that the flutter was not likely to happen, as explained above. They suggested specific procedures to check if abnormal behaviour or dynamically waving deflection, under extreme winds could occur. The two studies had different approaches: Wacker proposed to provide the wind load time series (wind load distributions function of time) to apply on the structure FE models for a time-dependant analysis. RDWI proposed to evaluate the dynamic loading amplification on the membrane to decide on the need for an aero elastic complementary test.

With this incertitude, trying to balance a conservative approach with a challenging one, the following deflection criteria was established for the rest of the design studies. In order to go under the usual limit of L/20 we plotted the deflection with respect to wind forces and probability of occurrence to visualise the non-linearity of the problem. The concept was to limit deflection for frequent wind and allow exceptional deflection under wind that have a long return time and that will not create wear since the reduced number of cycles. This study enabled us to reduce the deflection criteria to L/10 under characteristic wind load combinations (fluttering criteria), and L/20 only under frequent wind load combination (to avoid fatigue of the membrane under high deflection).



Fréquence des vitesses du vent enregistrées de 1987 à 1997 à la station météorologique d'Aubure (1 100 m, Alsace)

Wind case n°	Wind case	Speed (km/h)	Feels like *	Occurrences ** (days/year)
0	0% load	0 km/h	Nothing	0
1	2% load	14 km/h	Flags are floating in the wind	39,5% = 145 d/year
2	10% load	29 km/h	Branches of the trees are shaking	45% = 165 d/year
3	Frequent wind (20% load)	42 km/h	Electric lines and branches of the trees whistles	12% = 42 d/year
4	50% load	65 km/h	Hard to walk against the wind	3% = 11 d/year
5	80% load	83 km/h	Can't walk against the wind	0,4% = 2 d/year
6	Ultimate wind (100% load)	94 km/h	Tempest(kids could fly, trees could be uprooted)	0,1% = 1 d/year

** Feels like criterai is based on the Beaufort scale*

*** Occurrences are estimated on the wind frequencies recorded by the meteorological station in Alsace (Altidude 1100m), and the wind records in Bruges 2021 from the site meteoblue.*

Fig. 4: Wind loads analysis in Bruges area

2.3 Mesh orientation and behaviour of two different porosities

The unusual solution of orienting the fabric at 45° raised a new series of problems not encountered in standard design. Being oriented at 45°, the prestress cannot be applied differently on the short and long edge without deforming the mesh too much: the stress in one direction is a function of the other. It is therefore impossible to optimize the prestress on the base of the stiffer path, and the capacity of the mesh is determined by the less resistant of the two directions.

Having the same stress in the two directions but a different Young Modulus depending on the fabric creates uneven deformation along the seam between two strips of different porosity. The seam line will have an "S" shape after the application of the prestress, on the base of the stiffer path.

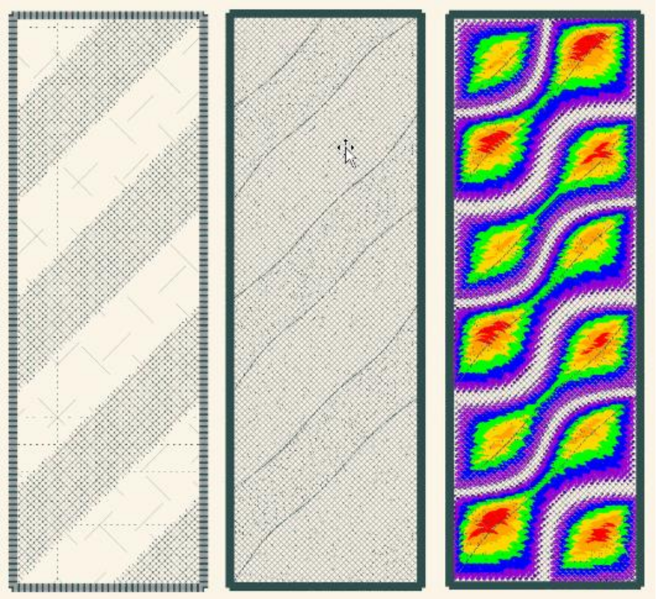


Fig. 5 : "S" shape deformation under initial uniform pretension

2.4 Detailing and load transfer

In order to reach the highest applicable prestress, and overcome the installation difficulties, special details were initially developed in order to avoid temporary stretches. The detail itself would serve as a temporary mechanism to apply the prestress.

Special attention was also paid to the loads transferred to the primary concrete structure, which were consequently also very high.

Considering the cost of such custom details and the excessive load take down on the concrete structure, a 8kN/ml pretension is not sustainable, and needs to be reduced for the final design.

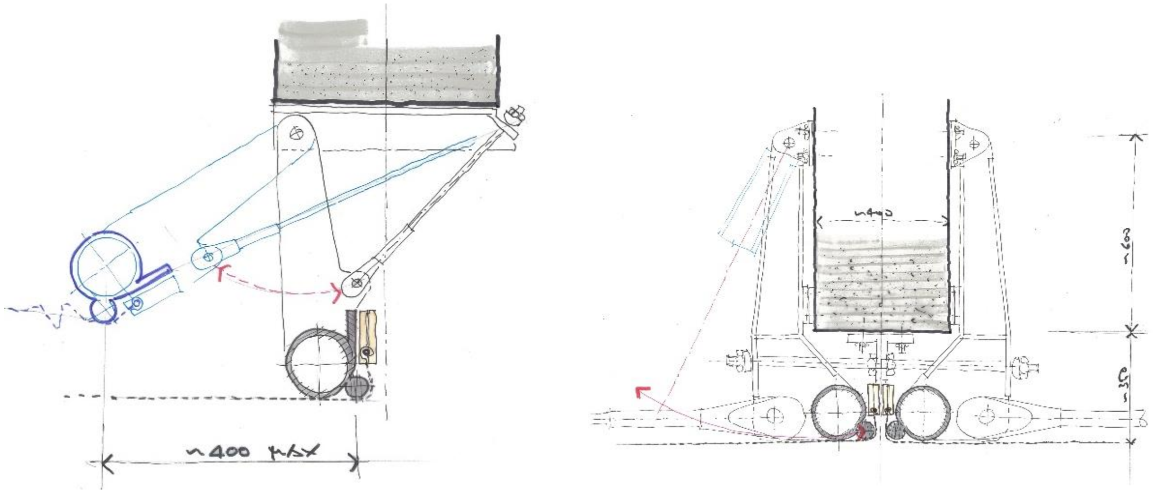


Fig. 6 : Designed details for prestress application and compensation

2.5 Conclusion on the initial design

The studies on the initial described design with 8x24m flat panels did not clear all the doubts on the design, because of several critical parameters:

- Prestress level too high to respect the deflection criteria and the dynamic criteria.
- Resistance of the porous fabrics
- Behaviour at the junction between two different porosities and uneven distribution of the prestress
- Compensation and fixing details

Considering these critical parameters that might lead to the impossibility of the project in the future, the full panels did not make good design sense. An alternative design, still challenging, was therefore developed, complying with the architectural brief and intention while reducing the required prestress.

3 FINAL DESIGN AND R&D

The new design was developed on the base of the following concepts:

<u>Architectural</u>

- Respect the architectural intents of a 45° pattern.
- Maximise the dimension of panels enhancing the linearity of the inclined strips
- Maximise the fabric span in order to reduce the visual presence of the supporting secondary structure.

Technical

- Reduce the required pretension to respect the deflection criteria and still avoid any dynamic behaviour issues
- Develop a highly porous fabric with a minimal resistance to fulfil the mechanical requirements of the project
- Get rid of the weakness due to the joints between different porosity fabrics
- Improve jointing detail in order to fully exploit the resistance of the fabric without stress reduction at joints

The solution for the new design was found with inclined strips, 6 meters wide and approximatively 35m long, of constant porosity. Each strips is composed of two bands of identical fabric jointed on the centreline by a welded seam. These diagonal panels or modules, delimited by the 6m strips, now replace the vertical flat panels.

Architecturally speaking, such a solution avoids any vertical joint, which would interrupt the inclined strips. The strip width of 6m still offers a visual lightness despite a secondary structure, as this latter is hidden behind the seam between two strips of different porosity. Technically speaking it also avoids joining two fabrics of different porosity on a same module: the transition in porosity are realised in the discontinuity of fabric at the supporting profiles of the secondary structure.

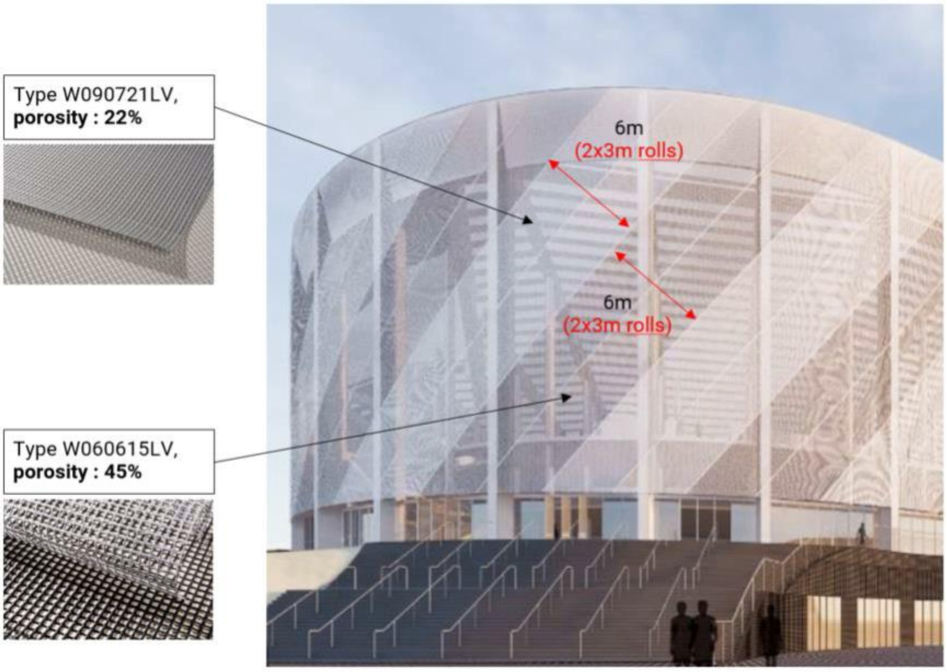


Fig. 7 : Alternating strips of different porosities on the façade

3.1 Development of a secondary supporting structure

3.1.1 Flexible and stiff secondary structure comparison.

The secondary structure follows the 45° diagonal strip, every 6m. Therefore, this structure spans on approximately 11m between two concrete columns, and supports the membrane cladding, whose warp direction is parallel to the structure. Span of the membrane cladding is therefore reduced to 6m and the prestress can be easily applied to the meshes in the weft direction.

The secondary structure can either be very lightweight and composed of cables or slightly heavier and composed of steel profiles.

With cables supporting the membrane cladding, a reasonable prestress is enough to respect the local deflection criteria of the membrane, but the global deflection including the deflection of the supporting cables requires an excessive prestress to achieve the global deflection criteria, inducing also high transfer loads on the concrete columns. Therefore, the selected design is composed of steel hollow profiles, anchored on the concrete structure, that are able to absorb bending moment without horizontal reaction forces on the columns.

3.1.2 Supporting structure strategies.

In tensile structure design, the supporting structure is only a tool to give shape to the membrane. Here the role is more complex and ambiguous since it is the transfer structure to the stadium concrete structure divides in 8 blocs separated by dilatation joints.

Different strategies have been evaluated:

i. A circumferential structure without joints conceived as “integral structure” which undergoes tension or compression under thermal loads. This solution implies a high interaction with the stadium structure and difficulties to separate the different tender packages between the main contractor (concrete structure) and the façade contractor.

ii. The second one consisted of a monolithic structure on sliding connections for each block of the stadium, accommodating the entire expansion at the dilatation joint of the stadium structure. This solution asks to vertically interrupt the membrane at every dilatation joint, which is not satisfying for the aesthetic qualities of the project.

iii. The third one consisted of introducing play at every bay to locally distribute the overall expansion. The small displacements are then solved in the steel connection and in the tension of the fabric. This solution allows an invisible dilatation joint in the façade, where the movement are resolved in the membrane thanks to a sliding fixation.

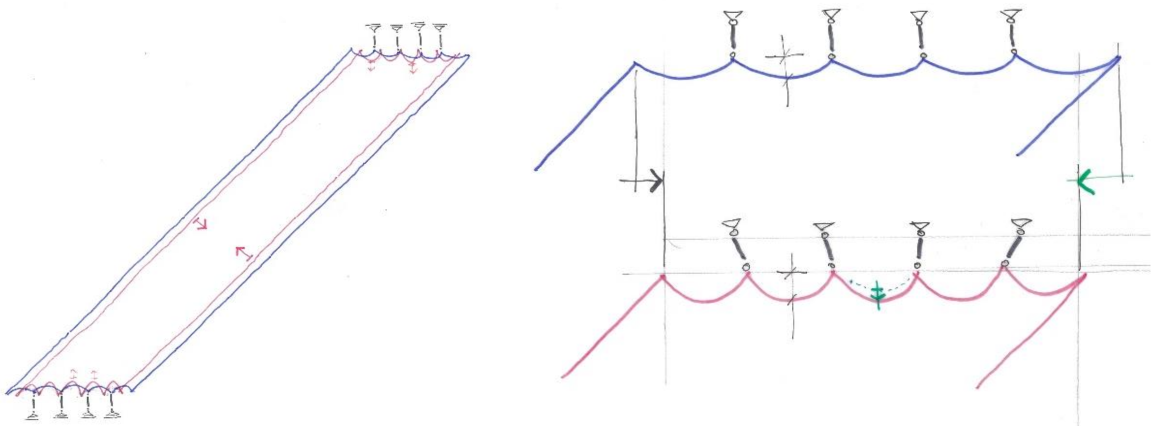


Fig. 8 : Local dilatation solved by the flexible membrane between two steel profiles

3.1.3 Final static scheme

As a result, the static scheme of the secondary steel structure is the following. The frame is decomposed into modules that group together 2 diagonal, and 2 strips of the same porosity. Each module is connected to the next one by a one-direction sliding connection, so that displacements due to thermal dilatation may be distributed evenly. The steel frame is anchored on the concrete columns every time the top / bottom beam meets the columns, as well as in the middle of each diagonal. Each diagonal is pinned only once on one of the coring columns, rest of the connection being sliding connections to ensure an isostatic scheme.

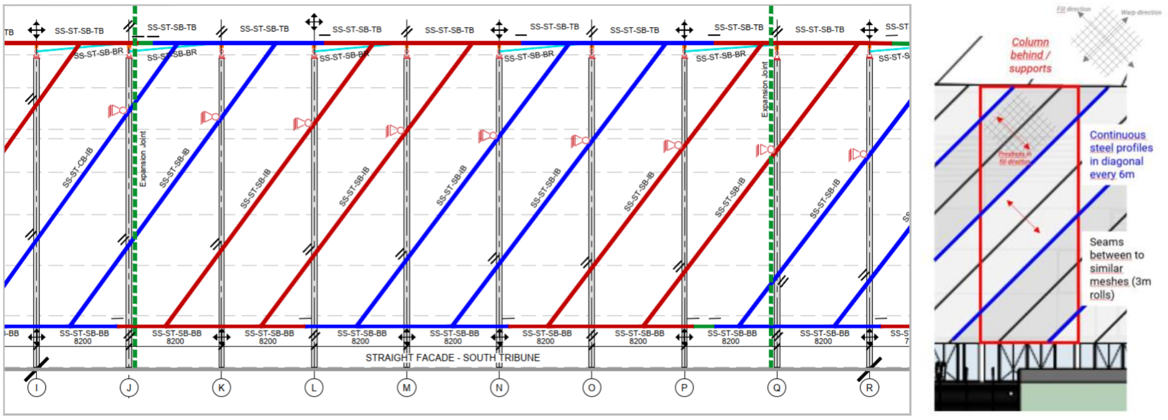
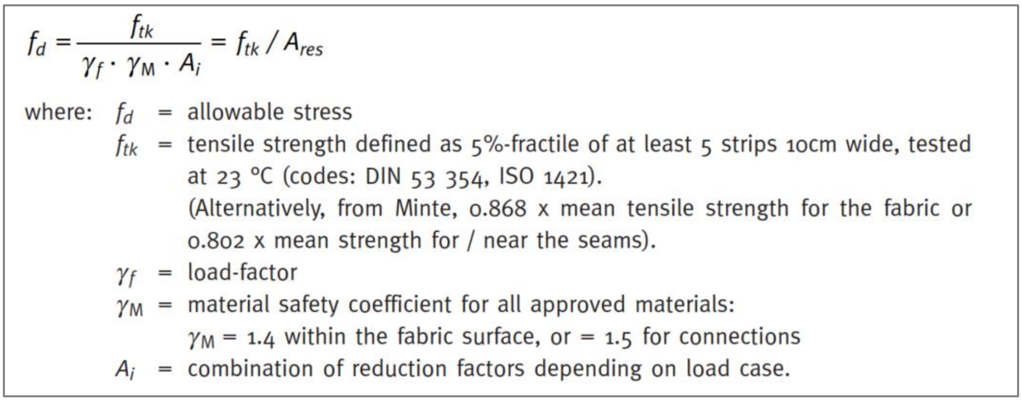


Fig. 9 : Static scheme

3.2 Development of a special textile mesh

To manufacture the 6m-wide strips, a welded seam joints two rolls on a central line. The seam is therefore stressed under loading of the façade. Not only should the fabric be able to support the stresses, the welded seam, which is the weakest point, needs to fill these requirements too.

The resistance of the membrane under external loads was checked according to the Method TENSINET [1] and the in progress future Eurocode for Membrane Structures [2]. Membranes are verified under SLS load combination, considering a safety factor on the material as defined bellow.



$$f_d = \frac{f_{tk}}{\gamma_f \cdot \gamma_M \cdot A_i} = f_{tk} / A_{res}$$

where: f_d = allowable stress
f_{tk} = tensile strength defined as 5%-fractile of at least 5 strips 10cm wide, tested at 23 °C (codes: DIN 53 354, ISO 1421).
(Alternatively, from Minte, 0.868 x mean tensile strength for the fabric or 0.802 x mean strength for / near the seams).
γ_f = load-factor
γ_M = material safety coefficient for all approved materials:
$\gamma_M = 1.4$ within the fabric surface, or = 1.5 for connections
A_i = combination of reduction factors depending on load case.

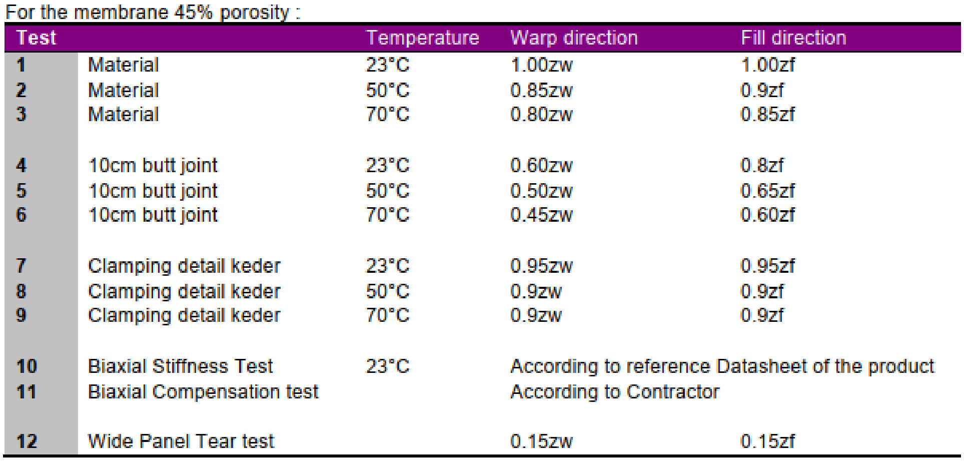
Fig. 10 : Extract of the Method TENSINET – Allowable stress and safety factor definition

The safety factor (and more precisely the *Ai* factor) depends on the load case that is considered: long or short term load or temperature of the load case for instance. Moreover a different behaviour is expected for the less resistant welded seam, hence a higher safety factor. Per default the safety factor for welded seams is very conservative and didn't provide the necessary resistance, especially for the highest-porosity fabric.

Thanks to a close collaboration with a textile manufacturer, a new fabric was developed for the need of the project, with a high porosity (45%) but a resistance and a young modulus close to the already existing less porous fabric (22%). These fabrics are Type II PVC membranes with high capacity PVC-coated polyester yarns, and the following tensile strength in warp/weft direction at 23°C :

- Fabric 1 (22% porosity) : zw/zf = 5000/4000 N/5cm
- Fabric 2 (45% porosity) : zw/zf = 5000/3800 N/5cm

R&D enabled to fulfil the following mechanical requirements to ensure the resistance of the seams and of other connection types, under different temperature cases. The welded seam is more precisely a butt joint of 10cm to guarantee enough PVC overlap and a good connection between the two pieces. These studies provide a more precise approach of the safety factor for the connections and the welded parts and allow therefore to consider a higher resistance for the welded seams and the cladding porous panels. The design of the butt joint was pre validated by a test done in the laboratory of the manufacturer.



For the membrane 45% porosity :

Test		Temperature	Warp direction	Fill direction
1	Material	23°C	1.00zw	1.00zf
2	Material	50°C	0.85zw	0.9zf
3	Material	70°C	0.80zw	0.85zf
4	10cm butt joint	23°C	0.60zw	0.8zf
5	10cm butt joint	50°C	0.50zw	0.65zf
6	10cm butt joint	70°C	0.45zw	0.60zf
7	Clamping detail keder	23°C	0.95zw	0.95zf
8	Clamping detail keder	50°C	0.9zw	0.9zf
9	Clamping detail keder	70°C	0.9zw	0.9zf
10	Biaxial Stiffness Test	23°C	According to reference Datasheet of the product	
11	Biaxial Compensation test		According to Contractor	
12	Wide Panel Tear test		0.15zw	0.15zf

Fig. 11 : Extract of the Specification of the tender package to ensure the quality of the connection and the resistance of the seams.

5 CONCLUSIONS

When the structural efficiency of tensile structure is confronted with a challenging architectural design, R&D and a close collaboration between the architects, the engineers and tensile manufacturers bring out a new and intelligent approach: while guaranteeing and reinforcing the architectural intents, the technical development and studies provide a new design and new solutions. Furthermore, this research and solution development hints at future design possibilities, maybe even more challenging.

Special Thanks to SIOEN and Maxime Durka.

This project would not have been possible without the contribution of the fabric manufacturers from SIOEN who, under the lead of Maxim Durka, supported the project along the whole design process and took the risk of developing a new porous fabric specifically tailored on the necessity of this project.

REFERENCES

[1] Brian Forster, Marijke Mollaert, *METHOD TENSINET – EUROPEAN DEISGN GUIDE FOR TENSILE SURFACE STRUCTURES (DIN 4134)*, 2004.

[2] Technical Committee CEN/TC 250 “Structural Eudocodes”, *Eurocode for Membrane Structures*, prCEN/TS 19102:2021-04, 2022