Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Flat membranes: Achieving dimensions using low strength porous fabrics

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Abstract

Most tensile structures take advantage of their 3D geometrical shape to balance tension forces and ensure their stability. However, the design approach is different for a flat membrane and its behaviour in big displacement non-linear regime. The project of Club Brugge Stadium, designed by SCAU and B2Ai, goes in this direction and offers a new challenge. The stadium is wrapped in a huge flat porous, tensile envelope. This façade is non conventionally conceived as a series of alternating strips of variable porosities, 45° inclined, creating a day and night zebra skin effect.

The transparency and relatively large dimensions between anchorages (over 8m horizontal and over 24m vertical) adds to the challenge a delicate interface between the façade and the main structure. Joining engineering skill and technical knowledge of tensile manufacturer brings out a new approach, where the research and development of a specific fabric is required to match the architectural intents while guaranteeing the structural and technical viability of the project.

Keywords: Tensile structures, Membranes, Large span facades, R&D

1. Introduction

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

Looking at the current planar tensile facades [1][2], the use of an independent and regular steel structural frame on which the membrane is clamped and prestressed, is usually preferred in order to deal with all the tensile stresses within this independent steel frame, and avoid high impacts on the main structure. The independent steel frame is then anchored on the main structure depending on the static constraints and specificities of the project.

As an example, for the Paris Olympic Games in 2024, the Town Hall of Paris has been decorated with membrane façade panels 5mx5m or 10mx10m, sharing the visual identity of the next games. This temporary installation will stay until the end of the Olympic and Paralympic games, and as the façade of the Town Hall is part of the national heritage, particular attention is paid to preserving the stonework on the façade. Consequently, all "destructive" anchoring in the facade deteriorating the stone is avoided:

the independent panels are dealing with the tensile stresses internally, and the steel structure is fixed on the existing stone façade with only compression jacks and elastomer supports in the windows frames.

Using an independent steel frame is less evident when the tensile façade is transparent, as it may tarnish the lightweight project's architectural image.

This paper relates to the study of 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 won the competition in 2020, and features flat tensile facades, with porous zebra strips of different porosity. A continuous vertical screen that wraps the perimeter 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 rainscreen. Thanks to its perforation and semi-transparency, it permits light to pass from both the inside and the outside, enhancing the effect of illumination. The membrane strips have an inclined layout and are organised with alternating porosity. To match the inclination of the strips of alternating porosity and ensure their manufacture, the warp and weft direction of the membrane is inclined at 45°. The screen's height varies between 17.5m and 24.5m and is supported by regularly spaced concrete columns that support the steel roof. Columns are spaced every 8.2m to 8.6m.

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

How to design a 24m high transparent façade when the primary structure is visible and arranged every 8m without tarnishing the architectural image of the project ? How to deal with the stress supported by a high dimension flat membrane, composed of a low strength fabric due to its porosity? How to design the relation between the façade and the primary structure? How to manage the dimensions of the slender primary structure with the tensile horizontal loads with the façade? These are the main challenges for the project.

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 presents additional technical constraints as the panels are composed of porous fabric, which has poor resistance, oriented at 45° and with welded seams joining strips with different porosities.

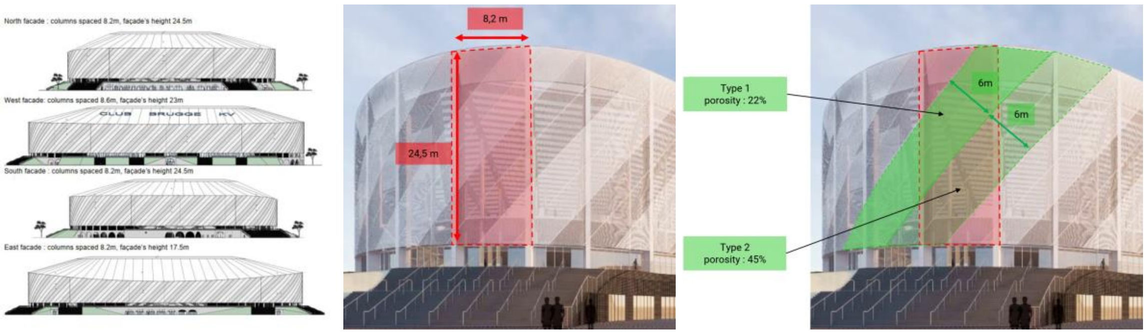


Figure 2 : Initial data and project constraints

2.1 Flat facades and high pretension

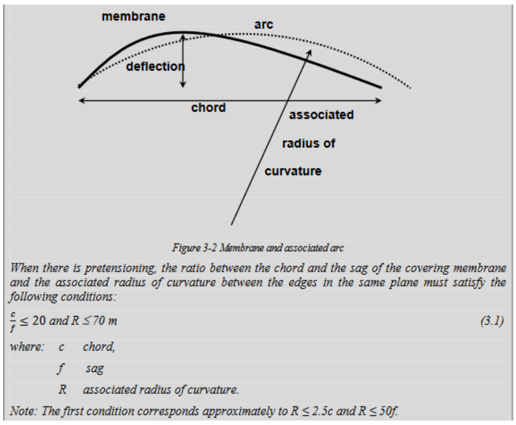
Flat panels need high prestress forces to stiffen the fabric with respect to orthogonal (wind) loads and enforce second order equilibrium. Excessive deformation leads to uncontrolled dynamic behaviour and should be avoided, hence a limited deflection (detailed in section 2.2). The theoretical necessary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

However, the resistance of the fabric already limits the applicable prestress. The fabrics used for the project, that have 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 stat of the art, manufacturers, and the contractors highly recommend not to work with a prestress higher than 2.5 kN/ml, with a large maximum of 5 kN/ml. A higher pretension is hard to master on site due to the big compensation, the detailing and the prestress procedure 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. Additionally, this 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 relate 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 [4], it is also possible to evaluate the stiffness of a tensile structure by knowing the static displacement (cf Fig 3.). 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.



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

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)

Figure 3: Extract of the Guideline for a European Structural Design of Tensile Membrane Structures Made from Fabrics and Foils [3]

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 exterior space, and the porosity balances the pressure without developing any dynamic airflow.

On the other hand, literature, and academic studies report that for particularly flexible membrane a wind study is required. The wind tunnel test specialist that were consulted at the time (Wacker and RWDI) had not performed this type of test before but agreed and confirmed that the flutter was not likely to happen. Eventual further dynamic studies (wind load time series for a time dependant analysis) or a complementary aero elastic test were suggested to support this conclusion if needed, and see if any abnormal behaviour or dynamically waving deflection were likely to occur, but have so far not taken place.

2.3 Mesh orientation and behaviour of two different porosities

The unusual solution of orienting the fabric at 45° raises a new series of problems never 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.

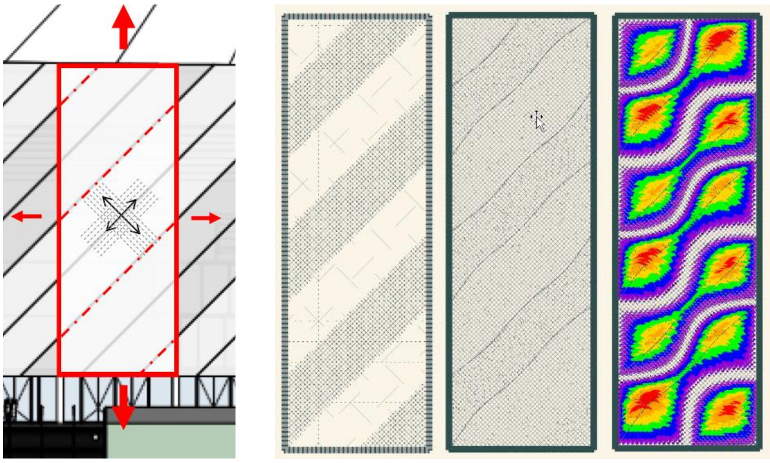


Figure 4 : “S” shape deformation under initial uniform pretension because of too different E modulus

2.4 Detailing and load transfer

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

The façade being transparent, the architectural image imposes the membrane to span between the primary columns and be directly anchored on the latter. Therefore, special attention is paid to the loads transferred to the primary concrete structure, which are consequently very high. Considering the architectural impact of the new dimensions of the columns, the cost of such custom details and the excessive load take down on the concrete structure, a 8kN/ml pretension is not sustainable. This solution was discarded in favor of design that minimizes the required prestress for the membrane stiffening effect.

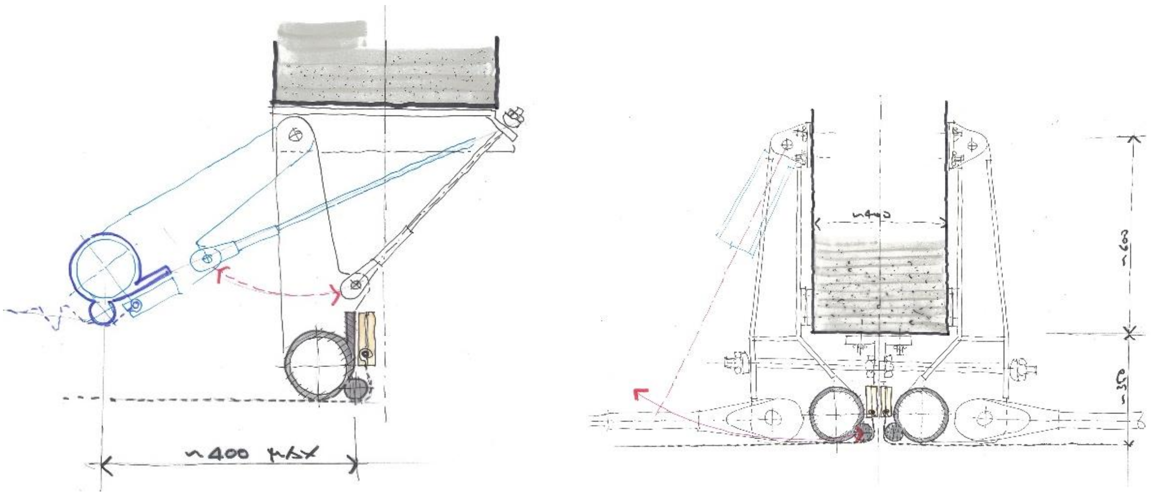


Figure 5 : Designed details for prestress application and compensation

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:

- Excessive prestress to respect the deflection criteria and the dynamic criteria.
- Low resistance of the porous fabrics (especially on the seams)
- S-Behaviour at the junction between two different porosities and uneven distribution of the prestress
- Non adapted compensation and fixing details
- Architectural image modifications (visible and prominent vertical joint between panels killing the wrapping effect, impact on the slenderness and dimension of the columns)

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, Research and Development

3.1 Adjusting the design strategy

The new design was developed on the base of the following concepts to match simultaneously the architectural and the technical requirements. Instead of working with big vertical panels, the new design would take advantage of the uninterrupted diagonal strips drawn by the alternating porosities. A secondary steel structure is designed following the diagonals and delimiting the 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.

Architecturally speaking, such a solution avoids any vertical joint, which would interrupt the inclined strips, and guarantee therefore the wrapping effect. The strip width of 6m still offers a visual lightness and transparency despite a secondary structure, as this latter is hidden behind the seam between two strips of different porosity, where a visual demarcation is unavoidable.

Technically speaking it also avoids joining two fabrics of different porosity on a same module, which is a difficult detail to master : the mesh size and fiber positions doesn’t match and they have different mechanical properties. The transition in porosity is therefore now realised in the discontinuity of fabric at the supporting profiles of the secondary structure. The span of the fabric is limited to 6m, reducing also the prestress level, and the prestress in the membrane is applied along one of the fiber direction (weft).

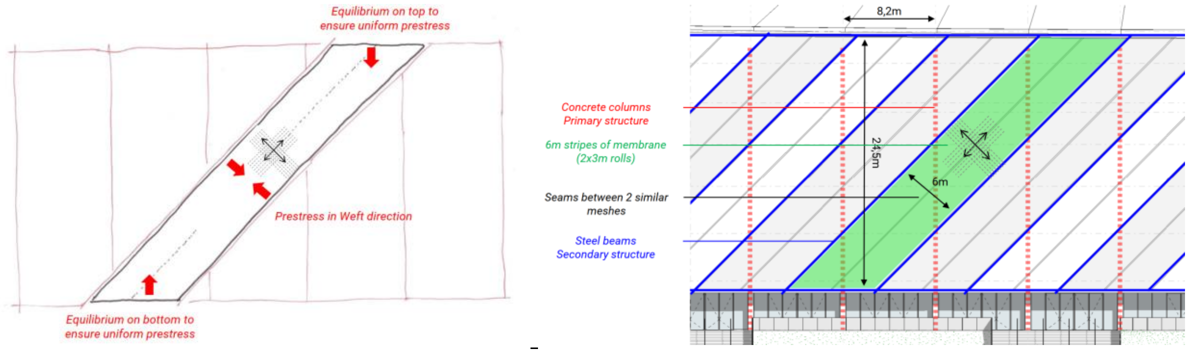


Figure 6 : New design strategy

3.2 Development of a secondary supporting structure

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.

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:

1) 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.
2) 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.
3) 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 is resolved in the membrane thanks to a sliding fixation. Additionally, a specific arrangement (Fig 8. Right) is designed at building joints that absorb the primary structure movements.

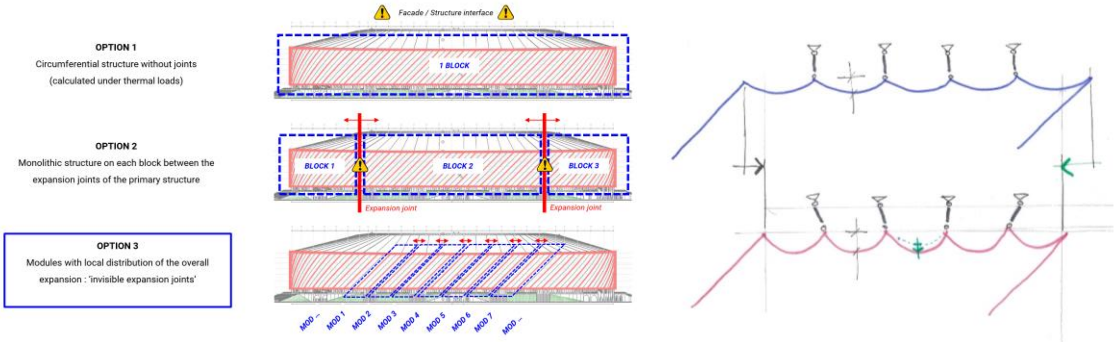
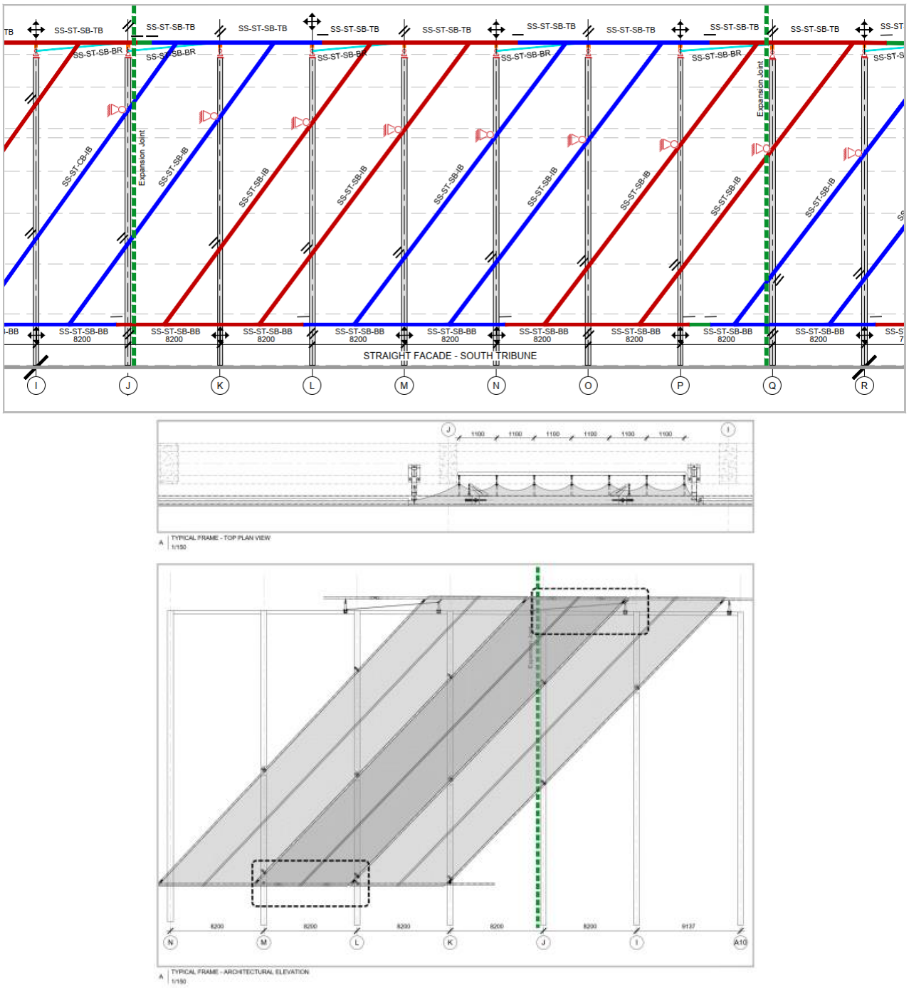


Figure 7 : (Left) 3 different strategies for thermal dilatation
(Right) Local dilatation solved by the flexible membrane on the building joints

As a result, the static scheme of the secondary steel structure is the following. The frame is decomposed into modules that group together 2 diagonals, 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 core columns, The rest of the connection are sliding connections to ensure an isostatic scheme.



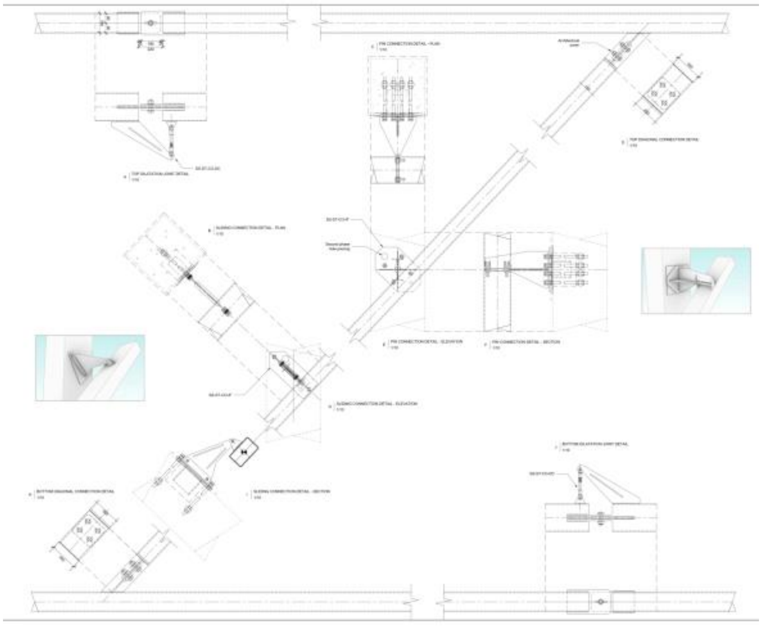


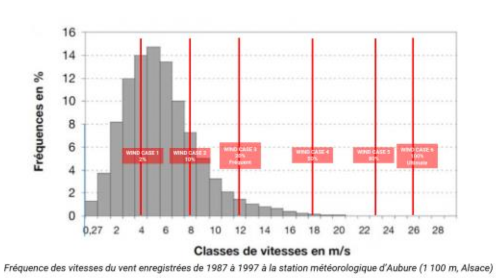
Figure 8 : (Left) Specific arrangement and details on a building joint
(Right) General steel details of the secondary structure

3.3 Development of a special textile mesh

Despite the span reduction, usual porous fabrics aren't capable to match the resistance and stiffness requirements described in part 1. For the needs of this project, a special fabric was developed.

<u>Stiffness and deflection criteria :</u>

Trying to balance a conservative approach with a challenging one, the deflection criteria was adapted and the following was established for the rest of the design studies. In order to go under the usual limit of L/20 the deflection was plotted with respect to wind forces and probability of occurrence to visualise the non-linearity of the problem. The concept is 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).



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.*

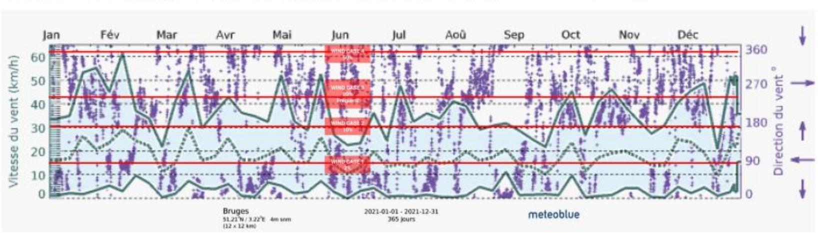


Figure 9 : Wind loads analysis in Bruges area

Tensile strength :

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 [4] and the in progress future Eurocode for Membrane Structures [5]. 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:
γ_M = 1.4 within the fabric surface, or = 1.5 for connections
A_i = combination of reduction factors depending on load case.

Figure 10 : Allowable stress and safety factor definition [4]

The safety factor, 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 for the design, especially for the highest-porosity fabric.

Thanks to a close collaboration with a textile manufacturer [6], 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. Unlike usual simple overlapping joints used in tensile structure, two full PVC closing strips encircle the membrane edges to be joined. 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

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

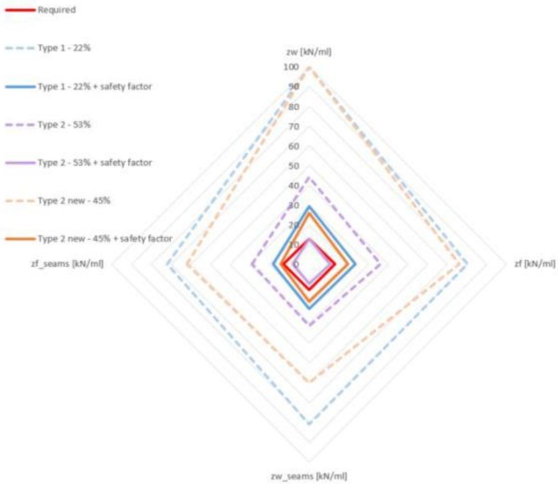


Figure 11 : Extract of the Specification of the tender package to ensure the quality of the connection and the resistance of the seams.

4. Conclusion

The project of Club Brugge Stadium challenges the engineering of a flat façade, porous and transparent façade with large dimensions.

The optimized design follows the movement naturally drawn by the uninterrupted strips of the architectural intent. A secondary diagonal steel structure allows 32m long strips, avoiding any previous vertical joint on the columns and reinforcing the wrapping effect. The study started analyzing wind loads to understand their implication in the membrane design. The static scheme of the secondary structure was designed to limit the impact on the primary structure, and ensure the compliance between the fabric, steel and concrete layers of the building. A special mesh was developed to achieve a 45% porosity mesh, resistant enough with respect to the efforts induced by the span and capable to satisfy the welding protocol of the seams as membrane detailing is as important as global static calculation.

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 brings out new and intelligent approaches and new design solutions.

Furthermore, this research approach and solution development hints at future design possibilities, within membrane design.

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