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TOPIC: IMPLEMENTATION – PARIS / AQUALAGON-VILLAGE NATURE / COMPLEX WOOD STRUCTURAL DESIGN

Jean-Marc Weill [1]

ABSTRACT: In the context of fitting out an holiday village at Marne-la-Vallée in Seine-et-Marne (France), "Les Villages Nature du Val d'Europe" entrusted the construction of the aquatic complex to the architect Jacques Ferrier. In Parallel we got the structural engineering design of the infrastructure and the superstructure of the buildings. it comprises three separate entities: the water pavilion including swimming pools (110x80 m with a maximum height of 27 metres), the air pavilion including including a tower with a height of 17 meters "Pavillon de l'Air" and the outdoor lagoon comprising pools creating a total bathing area of 2500 m2.

This document covers the analysis of the wood-steel accessible roof structure of the air pavilion and particularly the presentation of the assumptions adopted for the roof design. As a general view the uniqueness of this so-called large span structure is not to be a form-finding analysis with the very typical idea to find the best ratio between the volume of material and the span. At the contrary the shape of the surface is simply a consequence of its accessibility as a "promenade". This situation has led to a very unusual level of complexity regarding the engineering design also maximize by the use of a non-isotropic material such as wood.

KEYWORDS: Hybrid / Assembly / Humidity / Cross Laminated Timber

1 INTRODUCTION

Figure 1: *Perspective of the project / JFA Architect*

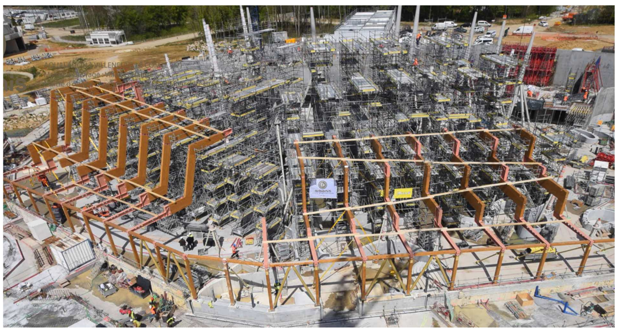


Figure 2: *View on construction site*

In the context of fitting out an holiday village at Marne-la-Vallée in Seine-et-Marne (France), "Les Villages Nature du Val d'Europe" entrusted the construction of the aquatic complex to the architect Jacques Ferrier. It comprises three separate entities: the water pavilion including swimming pools (110x80 m with a maximum height of 27 metres), the air pavilion including including a tower with a height of 17 meters "Pavillon de l'Air" and the outdoor lagoon comprising pools creating a total bathing area of 2500 m2. This document covers the analysis of the wood-steel accessible roof structure of the air pavilion and particularly the presentation of the assumptions adopted for the roof design. As a general view the uniqueness of this so-called large span structure is not to be a form-finding design with the very typical process to find the best ratio between the volume of material and span. At the contrary the shape of the surface is simply a consequence of its accessibility as a "promenade". This situation has led to a very unusual level of complexity regarding the engineering design also maximize by the use of a non-isotropic material such as wood. The paper is broken down as follows:

- A- Design process assumptions
- B- Analysis of the stability
- C- Modelization and calculation.
- D- Innovation in wood connexions
- E- The Fire stability question

[1] Jean-Marc Weill Architect / Engineer, Principal of CE-I consulting engineers-Paris (France), Faculty: Professor at the ENSA-VT (Ecole Nationale Supérieure d'Architecture de la ville et des Territoires) / Paris, weill@ceingenierie.fr

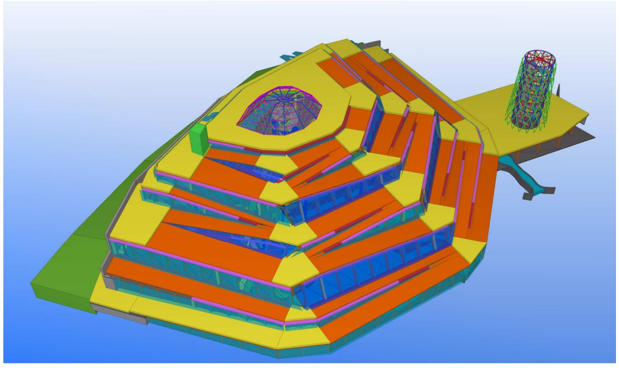


__Figure 3:__ Three dimensional ramp design of the roof.

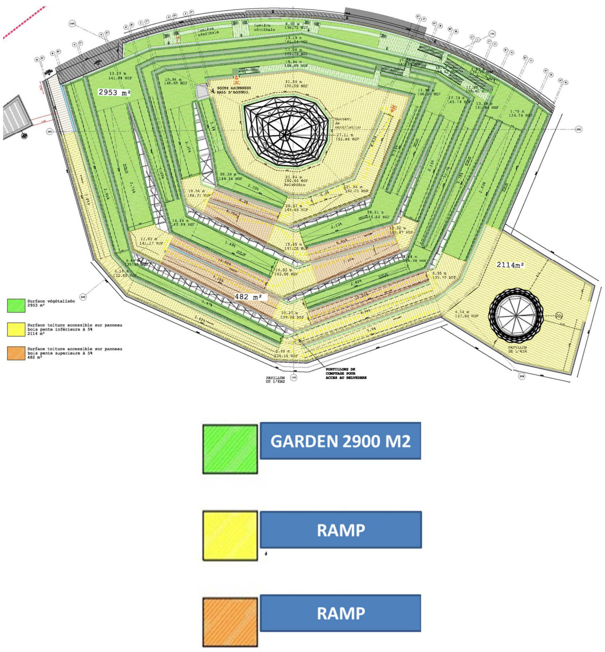


***Figure 4:** Garden an ramp*

2 DESIGN PROCESS ASSUMPTIONS

This paper aims to suggest a view of the design process based on the use of technology and structural knowledge, and to propose a model for the inherent architectural design method. The specific objectives are broken down as follows:

- How the differences between design objectives and technological constraints (such as the machine, the materials and the construction process) affect the quality of the object itself?.

- What principles on the use of technological knowledge can be suggested by this case study?

3 DESCRIPTION DU DISPOSITIF

3.1 GEOMETRY AND ELEMENTS

Overall coverage of the water pavilion is an extension of the walk to the lookout at the top of it. Accessible to visitors, it consists of a succession of ramps and glass walls of irregular shape.

The project roof is a wood marquee "resting" on the surface to be covered. The marquee comprises a primary structure, consisting of a radiating frame and a second structure following the circumference of the main structure, with the final result forming a random surface structure following the extension of the access ramps to the roof. On this hypothesis the primary structure is designed as follows:

- Formed mixed joists and wood studs Glued Laminated steel and triangulation forming a serie of irregular truss beams. They are located behind the glass surfaces.
  - → Change heights : 60cm to 650cm
  - → Amplitude of the spans : up to 28m
  - → Section of horizontal members : 2x 150x400mm
  - → Section of vertical members : 260x400mm

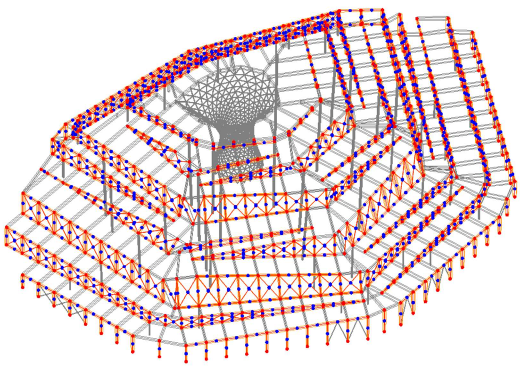


***Figure 3:** Axonometric of the truss beams*

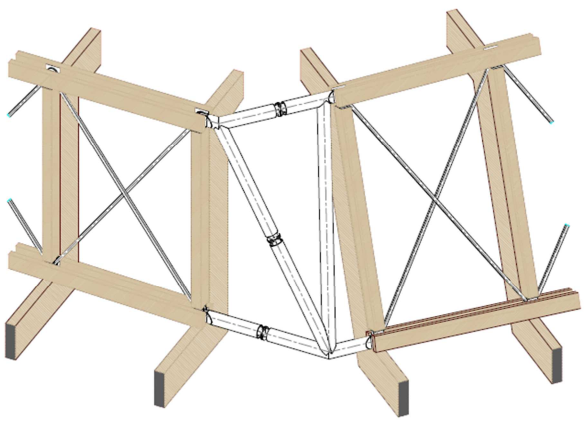


***Figure 5:** Detail of the variation of geometry*

Figure 6: *View on construction site*

- Radial beams made of laminated wood glued continuous floor-to the central core of the pavilion. Visible from inside the Aqualon , these elements are located to the underside of the cover. Continuity is performed on site with steelwork connexion or at the factory by the implementation of glued studs. They participate in the stabilization process producing the “shell” effect.
  - → Number : 52
  - → Maximum length: 45m
  - → · Section : 26x90cm

The structure of the roof rests on wooden posts on the front and on concrete High Performance column located in and positioned by referring to the interior, that is to say, randomly accordingly random supporting structure of the roof.

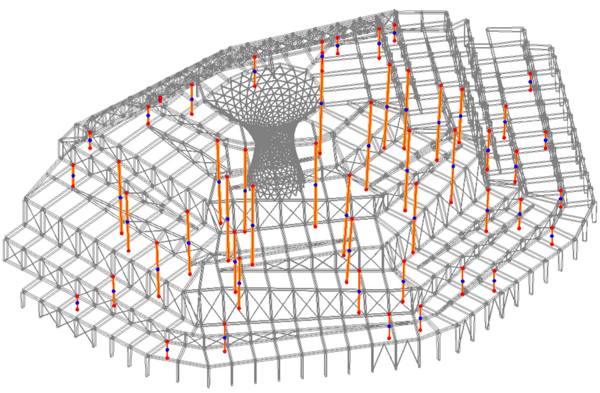


Figure 7: *Axonometric of columns*

Figure 8: *View on construction site: the columns*

The central core: central element of the project, supporting a glass roof, the wooden ramp system and the staircase of access to water slides.

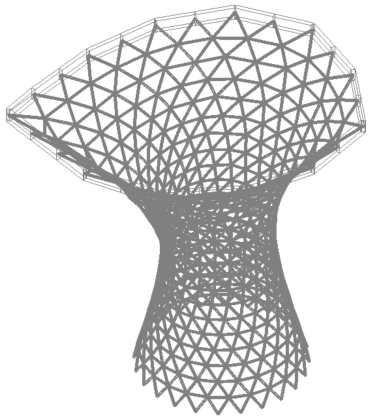


Figure 9: *Central core of the building*

3.2 SHELL EFFECT

Outside the singular points, the transfer of vertical and horizontal loads to the foundation is done by the Association of the truss frame and the radial beams . The combination of the radial structure and trusses confers rigidity to the structure ("shell effect") .

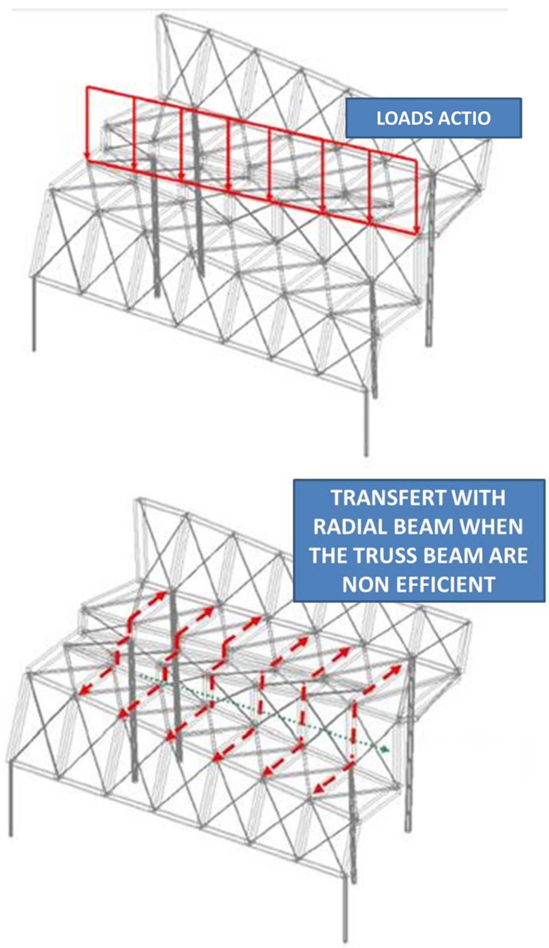


Figure 10: *Example of load transfer*

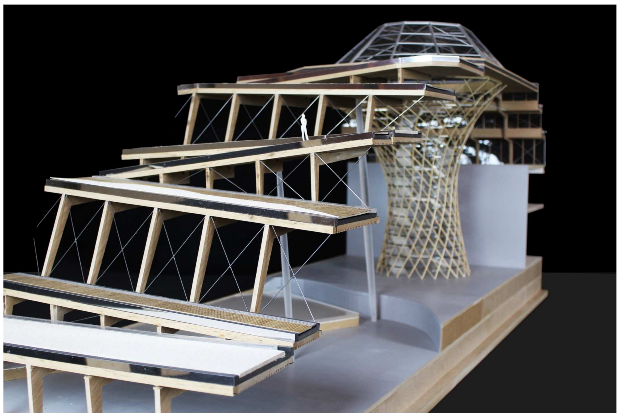


Figure 11: *Study model by JFA Archutect*

3.3 THERMAL DILATATION

Given its geometry the roof is designed without expansion joints. It thus spans the infrastructure expansion joints in reinforced concrete. This assumption led to leave the free volume to expand out of its plane under the action of heat loads in particular, by placing on the ground floor façade pendulum columns for horizontal expansion.

The facade of the Ground Floor is then designed to be fixed to the primary framework and follow the movements. At the rear of the building, the interface with the concrete block is done by sliding support for not curbing the expansion of the superstructure

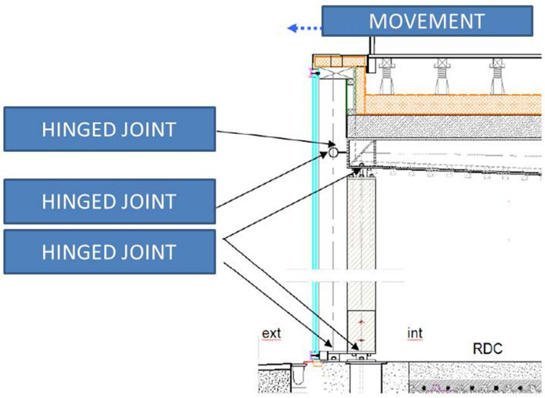


Figure 12: *The column connexion at the ground floor*

3.4 MATERIAL

Wood has implemented the following mechanical characteristics:

- Laminated Glued wood Class GL24H / GL28H , according to the EN14080 standard NF.

4 MODELIZATION

4.1 OVERALL MODELLING

Modelling takes the form of a non-linear calculation conducted using the Sofistik software application. The entire roof structure was modelled using bar elements with the exception of interlocking beams at some ends of the truss beams, which were modelled using surface elements.

4.2 INPUT FOR CALCULATION

The following elements were used as input for the calculation model:

- Fibrous concrete posts: bi-articulated elements which only absorb normal forces.

- Truss beam upright and frames in glued laminated timber: continuous or articulated bar elements depending on the position. These elements support the windows which mean that the erecting tolerance of the curtain wall becomes the reference for the wood structure.

- Diagonal truss beams: steel tie rods.

- Radial glued laminated timber: continuous elements over one or several levels depending on the position of the resting points. The elements contribute to ensuring the stability of the roof shape and supporting the ramp decks. The calculation model incorporates the rigidity of the assembly. The elements are assembled with glued bolds.

- Decks in cross laminated timber: the diaphragm effects of the deck are modelled using triangulations of wire elements in order to analyse the behaviour of the structure.

- Central drum: triangulated structure in glued laminated timber and horizontal steel straps.

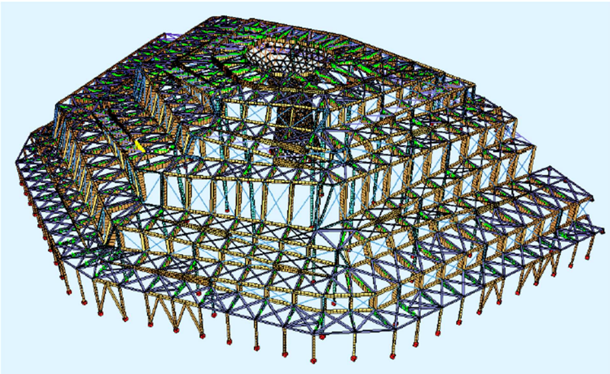


Figure 13: *Three dimensional modelization*

The horizontal bracing consists of a stepped diaphragm comprising horizontal planes in cross laminated timber panels and truss beams.

This stability plane is separated from the radial beams loaded to ensure the stable shape of the structure.

Modelling is established on this basis. Horizontal forces are mainly transferred via the vertical stability support structures located in the lower part of the first ring and in the triangulated central drum. Vertical bracing is ensured by stability support structures positioned in the pool side of the façade and by the reinforced concrete structures hosting the equipment for the overall structure.

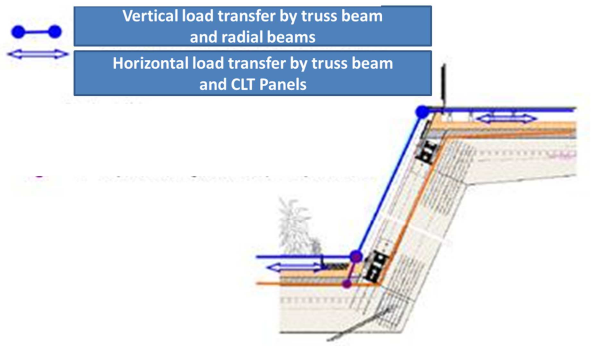


Figure 14: *Load transfer principle*

4.3 WOOD SERVICE CLASS STRATEGY

The purpose of this chapter is to discuss the potential impacts caused by the change in wood service class (switch from class CS1 to class CS2 regarding Eurocode recommendations). This discussion was asked, on a conservative basis, by the Customer, regarding the typical interior humidity of such a program even if it was possible, from an analytical point of view, to retain the CS1.

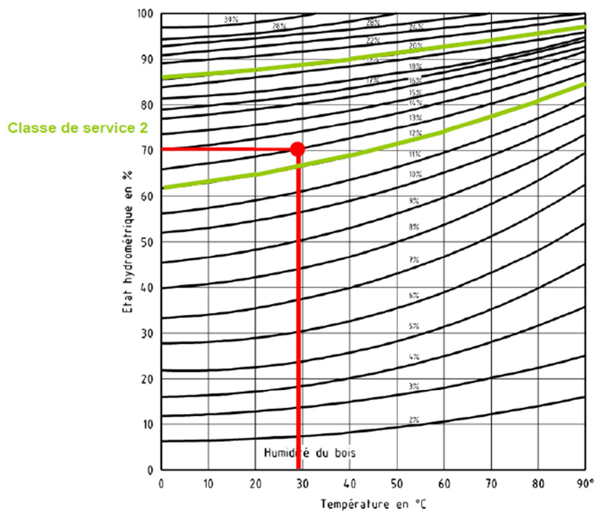


Figure 15: *Wood service class*

The analysis had the following targets:

- Comparative analysis of stress variations in wood/steel sections subsequent to the change of service class.
- Analysis of the compatibility of the width of the windows and new strain in the truss beams supporting the windows in view of assembly slip and wood creep.
- Modification of the execution order subsequent to the change of class.

The change in service class will increase strain in the truss beams and their appropriateness for the dimensions of the windows. The curtain wall recommended is designed with stiffeners in glued laminated timber and aluminium mullions structures.

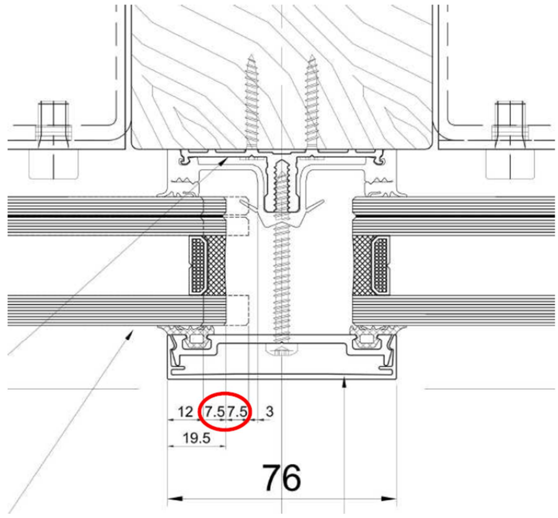


Figure 16: *Window frame available joint*

On a precautionary basis, the acceptable slope between two vertical members of the truss beam is limited to 5 mm per window. In order to apprehend the strain which the façade must absorb, we had to analyse two successive states of the wood frame:

- the strain state of the truss beams before the installation of the windows Uinst, Gmin including the specific weight of the roof complex and the earth removed.
  - → This state will be our "reference point 0" when calculating the impact of strain on the windows.
  - → final state Ufin, G+Q+N

The difference between the two states gives strain value so called U3, which the façade must absorb throughout the life of the building. The following method is used to analyse each truss beam for the project:

- Determination of absolute displacement U3 next to each upright.
- Determination of variation in gradient subsequent to displacement next to each upright.
- Comparison of the gradient thus obtained with the allowable gradient per type of window length (1 m, 1.5 m, 2m, 2.5 m).
- Punctual adaptation of the length of the windows planned during the project stage (reduction) on the basis of these results.

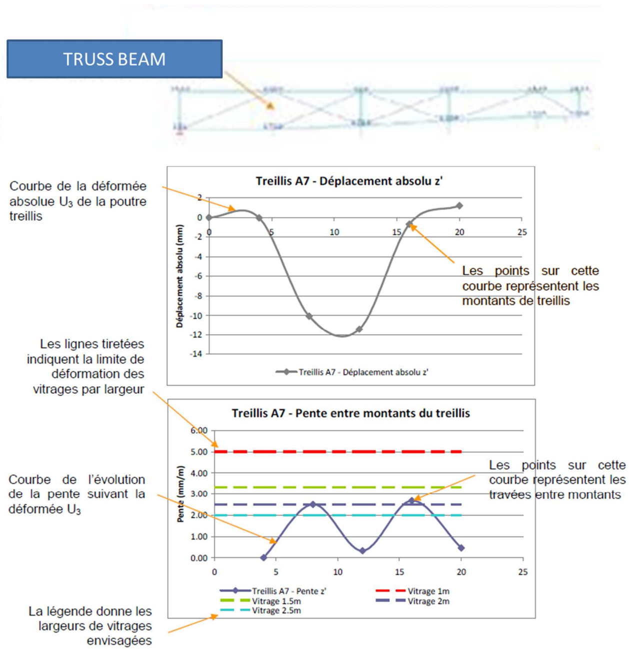


Figure 17: *Analysis of the slop of the truss beam regarding the length of the window.*

The main results obtained, on the basis of the model created by the design team, are as follows:

- The switch to service class CS2 only has a very moderate effect on forces in the building frame components and does not modify the sizing of the contract documents.

- The switch to service class CS2 punctually redistributes the lowering of loads between resting points by 15% (on the basis of the comparative analysis of the Project management model). This value is substantially lower than the global increase coefficient integrated by the Company for the transmission of lowering loads in order to integrate all possible modifications.

- The switch to service class CS2 and the integration of assembly stiffness affects the strain on truss beams, as expected. The width of a few windows must be reduced in order to globally comply with allowable rear structural gaps, limited at 5 mm by the Company.

The modification inherent to switching to service class CS2 aggravates the factor Kdef (strain coefficient according to Eurocode 5). The coefficient is now 0.8 (versus the 0.6 initially planned for service class 1).

5 FOCUS ON STRUCTURAL DESIGN

5.1 FIRE ANALYSIS

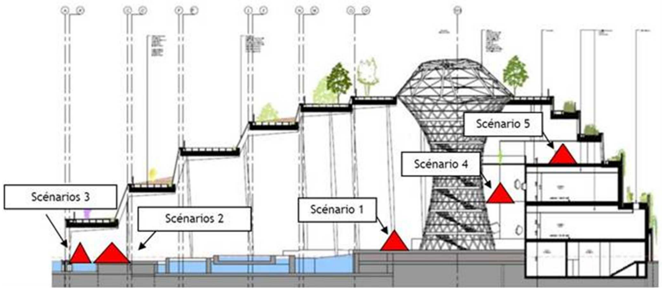


Figure 18: *Fire scenario accepted by the client*

With reference to decks, the aim is to calculate the resistance of the panel after removing the carbonated thickness based on real fire analysis. The calculation was developed with the laboratory Efectis on the basis of scénari defined with the client. Efectis applied the following method: Classify the structure into 3 sub-assemblies according to the following criteria:

- Thermal Flux < 3 kW/m² : no consequence on Wood structure;
- 3 kW/m² < Flux < 8 kW/m² : the wood structure must be calculated within a section reduced.
- Flux > 8 kW/m²: Risk of fire wood and fire spread, if not acceptable => reinforcement / protection / modification structure or operating constraints to limit risk.

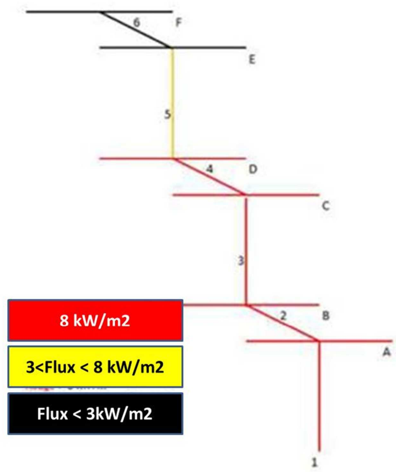
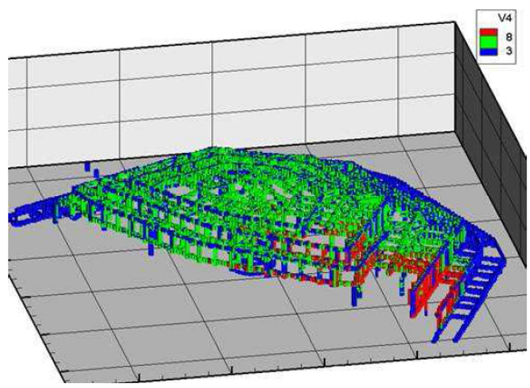


Figure 19: *Typical transverse vertical cross section.*



5.2 ASSEMBLIES BY GLUED DOWELS

5.2.1 General principle

From a general point of view it includes :

- The transmission of forces between uprights and radial beams by contact.

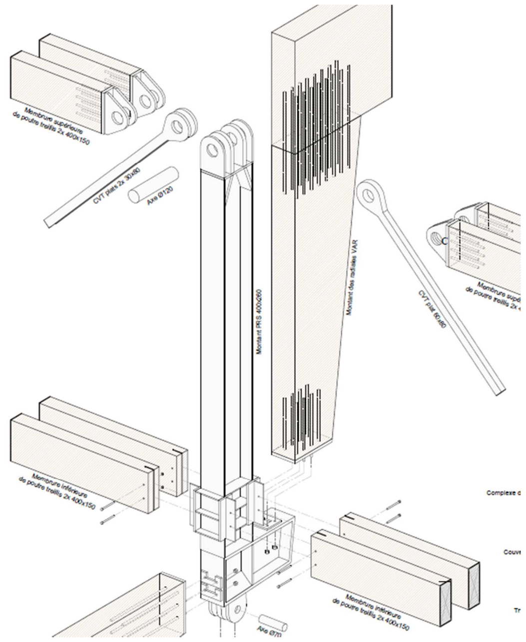


Figure 20: *Axonometric of the assembly of the radial beams*

5.2.2 Les assemblages par goujons collés

The assemblies by glued dowels concerns the assembly of radial beams . They used to reconstruct the geometric continuity of the assembled elements therefore like broken beams.

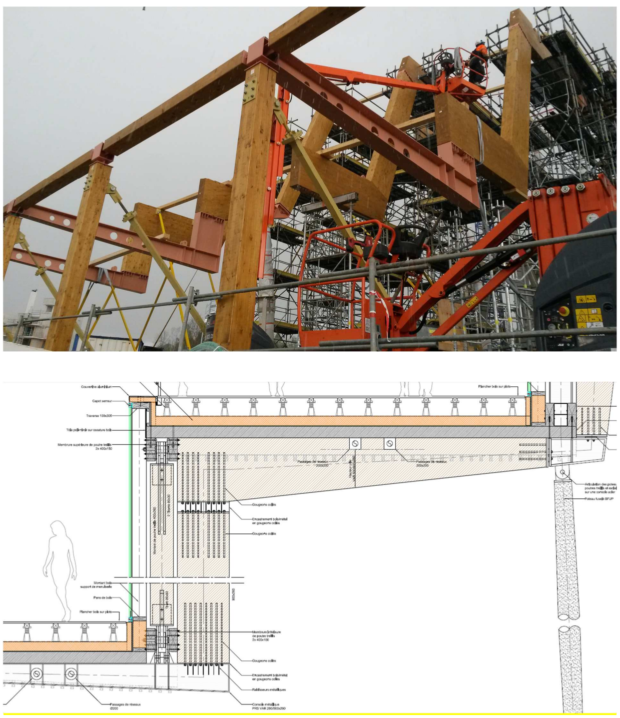


Figure 21: *Site view and elevation of an assembly*

This device is intended for assembly embodiment in new construction. The bonded stud system allows assembly of elements wood structure between them and with other structural elements. These assemblies can be subjected to axial loads and / or transverse.

The resins used for injection and pasting wooden steel rods are made on the same epoxy resin bi component tradename Eponal 316 TH, distributed by the company Bostik S.A. The manufacture beams and the sizing operation are carried out exclusively at the factory.

The mechanical assembly of this type of performance is established on the basis of characterization tests.

The studs are composed of a threaded rod, two nuts and a centering system. They are treated as required by the environment in which the implementation will be. For the construction of Aqualagon threaded rods and nuts are galvanized.

Figure 22: *Testing Process*

Machining is composed of a bore for the introduction of the threaded spindles, a countersink for the establishment of a centering nut, and two vent holes for the injection of the resin (an injection hole and a degassing hole of either side of the bore) .

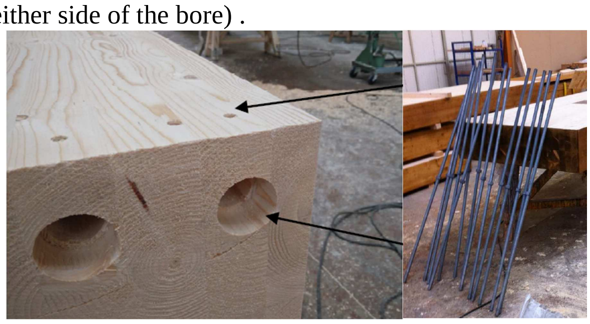


Figure 23: *Testing Process*

5.3 CLT PANEL GRADIENTS

When preparing the working drawings, the design and construction team suggested using KLH panel gradients incorporated in the solid base. The slope shapes of KLH panels in the solid base has no effect on the overall design of the support panels for the roof set-up. The panels, with a width of 240 cm, will have a 3% external gradient, reducing the low point section to a thickness of 190 mm.

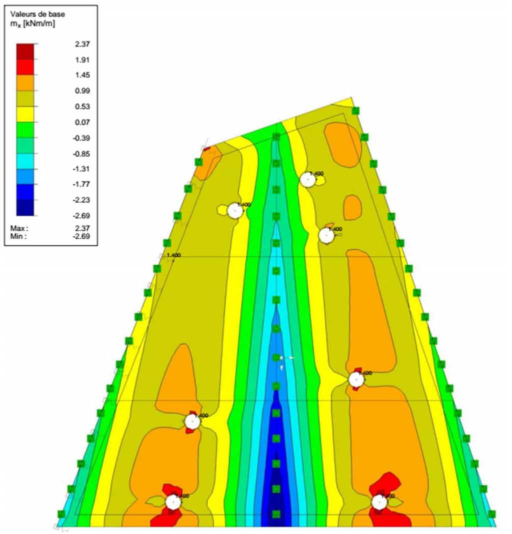


Figure 24: *Finite element analysis by KLH regarding the holes in the panels*

When justifying the panel, we have assumed a minimum useful section with consideration of the upper and lower folds in the direction of load bearing between radial beams, i.e. 4 metres. The reduced section panel considered for the calculation is equivalent to a 162 mm panel (and not 190 mm) in order to correspond to the DTA (Technical approval) for the product.

5.4 ROOF COMPLEX

In France the use of KLH panel as hedges is now limited to a job on average humidity (ie < 5 g of water per m3 of air) . The use of the panel in medium to very high humidity forced to perform calculations coupled transfers of heat - moisture through the materials of the roof system. The humidity and temperature conditions of the various materials are obtained from calculations made with the software “WUFI." which can simultaneously simulate heat transfer, water vapor and liquid wate .

The simulations were performed over a period of three years to a room located in Trappes (78) in the Paris region (the project being carried out at Marne-la- Vallée, the nearest weather station including all data required simulations is that of Trappes) . Assuming a ventilated air gap , it is considered very strongly ventilated , temperature and relative humidity are then identical to those of the original atmosphere of the ventilation flows. The air transfers are not included. The rain- movies or vapor are considered continuous, without drilling holes .

The practical significance of the results can be interpreted by different methods:

- Comparing the hydrothermal conditions obtained with the specified limits
- By controlling the risk of moisture accumulation. The evolution of the total water content in the construction will be assessed by comparing the value to the original that after a cycle ;
- - Assessing the moisture tolerance of construction (potential drying) ;
- - By treating transient results with post-processing model (eg for the development of mold or algae, rot, corrosion ...) .

The first element to be checked is the water content of the wall in its entirety. If it increases significantly from one year to the other, it means that the hydrothermal transfers in the wall are not stable. The water content of the wall could increase beyond the three years of simulation and lead to significant condensation.

A wall, to be satisfactory, may not contain elements whose relative humidity is above 98%, even in specific locations of the wall. In effect the software tolerances mean that beyond 98%, the risk of condensation may be considered very likely.

Similarly, the water content of an element of the wall containing biobased products may be occasionally (less than 8 weeks per year) exceeds 23 mass% (this limit of 23% is based on work laboratory and on recognized and successful experiences, taking into account the various conditions of germination of spores). It should be noted that the 8-week beyond 23% is unfavorable, even if reached discontinuously. Periods beyond 23% lower than a week will not be counted, not being long enough to cause fungal growth.

The graph below shows the acceptability of a constructive solution based on the elements outlined above .

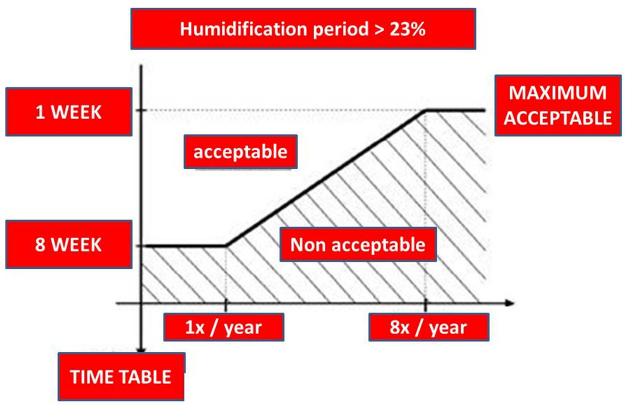


Figure 25: *acceptability of a constructive solution*

Another property influencing the behavior of moisture biobased material is its ability to be able to contain both free water and / or water related. Water is called bound or hygroscopic when it is "restraint" chemically (hydrogen bonds) by the wood fibers . The water molecules are then fixed in the material itself. The free or capillary water, so liquid, appears in the wood when the moisture content (in mass%) exceeds the saturation point of the fibers. For the main softwood species used in structure, the point of fiber saturation is reached when the wood moisture content exceeds 30% by mass. The calculation case where moisture of wood or wood-based materials (panels, insulation) exceeds 30% will therefore also be a knock-out test, the liquid water in a closed wall is very difficult to evacuate.

The input parameters for each component are:

- The resistance to diffusion of water vapor (μ , dimensionless)
- The sorption curve (change in water content of a product balance in environments with different moisture contents) ,
- Thermal conductivity,
- The specific heat,
- Porosity,
- The density.

The studied configuration is the configuration A

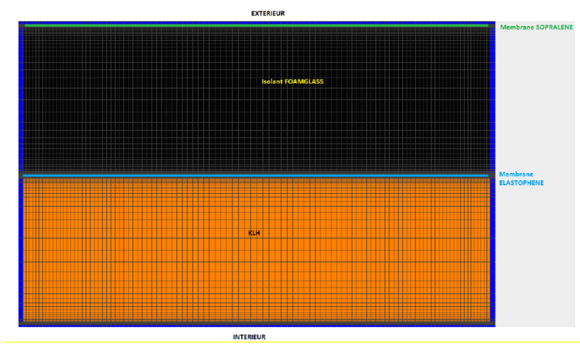


Figure 26: *section modelized for the analysis / CSTB document*

Roof slope of 3 to 5%

- Decking wood 30 mm thick,
- Joist wood 60 mm thick,
- Sealing SOPRALENE FLAM ,
- Insulation Foamglass T4 160 mm thick,
- Vapour ELASTOPHENE 25
- CLT/KLH e=160 mm

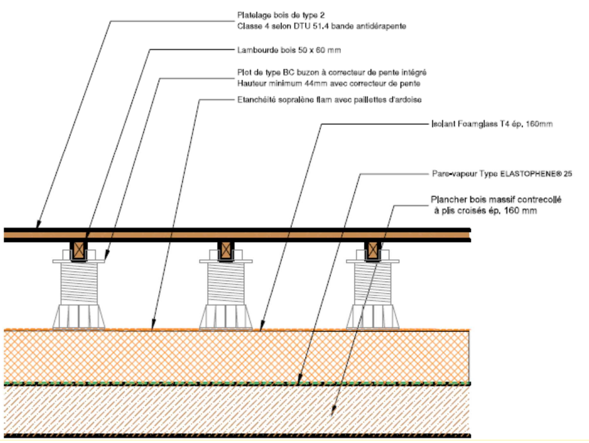


Figure 27: *Built floor section*

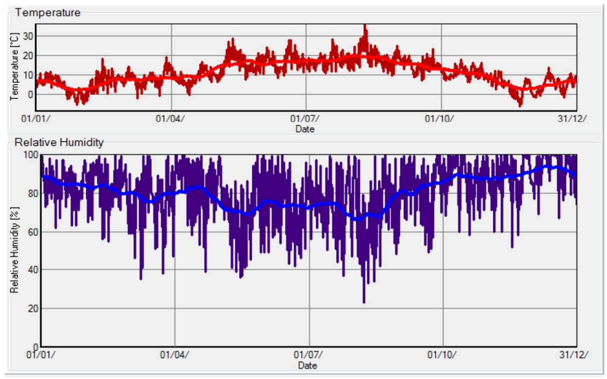


Figure 28: *Variation of temperature and humidity during a year on site*

The interior includes various relaxation areas and swimming pools. Indoor climate, indicated by the applicant as the reference atmosphere defined by the prime contractor, is 29 ° C and 60 % RH (hypothesis 1). To validate the warranty of the system simulations were also conducted with internal conditions of 29 ° C and 75% RH (hypothesis 2). This last atmosphère was advocated by the applicant.

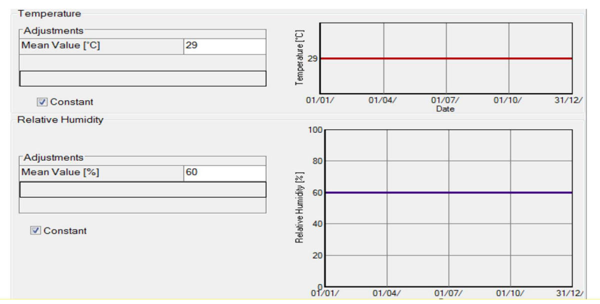
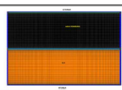


Figure 29: *Variation of temperature and humidity during a year inside of the building / CSTB document*

N°	Schémas	Système	Valeur Sd de la membrane ELASTOPHENE en m	Valeur Sd de la membrane SOPRALENE en m	Climat extérieur	Climat intérieur
A3		Toiture pente comprise entre 3 et 5%	179,4	100	Trappes	29°C et 60%HR
A4		Toiture pente comprise entre 3 et 5%	179,4	100	Trappes	29°C et 75%HR

a) Configuration A

Cas de figure	Valeurs maximales atteintes à la 10ème année	Teneur en eau en kg/m³	Teneur en eau % en masse	Humidité relative en %	Evolution au cours du temps
A3	Paroi Globale	21,9	_	_	↘
	KLH global	44	10,4	67	↘
	Partie du KLH contre la membrane ELASTOPHENE	51	12	74	↘
A4	Paroi Globale	31,9	_	_	→ Faible croissance
	KLH global	63,8	15	83	→ Faible croissance
	Partie du KLH contre la membrane ELASTOPHENE	80	19	91	→ Faible croissance

Tableau 3 : Synthèse des résultats de calculs - CONFIGURATION A

Figure 30: *Analysis of the volume of water inside of the complex / CSTB document*

When the inner atmosphere is 29 ° C and 60% RH, the average water content of the wall decreases over time to achieve, during the tenth year, 22kg / m3.

By analyzing the first millimeters of KLH in contact with the ELASTOPHENE membrane, the water content of this part of KLH (the most exposed to condensation) is 51 kg / m3, a water content in% by mass of 12% and a relative humidity below 74%. Under the provisions outlined in the "Results Interpretation of Rules" (see Annex 1 below), considering the continuous waterproofing membranes, without perforation and with a constant internal environment and equal to 29 ° C and 60% RH , the wall is of no liquid water accumulation; no condensation were reported and the water content in mass% is not sufficient to create a fungal development. This applies to all products constituting the wall, including the most stressed part of KLH. When the inner atmosphere is 29 ° C and 75% RH, the average water content of the wall increases slightly over time to achieve, during the tenth year, about 32kg / m3. The water content of the product KLH also increases slightly over time to reach 64 kg / m3 at the end of the tenth year. By analyzing the first few millimeters of KLH in contact with the ELASTOPHENE membrane, the water content of this part of KLH (the most exposed to condensation) reached 80 kg / m3, a water content in% by mass of 19% and a relative humidity below 91%.

These values increase slightly over time. Trying to extrapolate the different curves at 20, the product KLH as a whole (average values) would reach a water content and relative humidity to respond positively to all criteria. But, for the part of a few millimeters of KLH located against the vapor barrier, the simulations could approach a water content by mass% of 23% or even exceed it. The relative humidity should be around 98%.

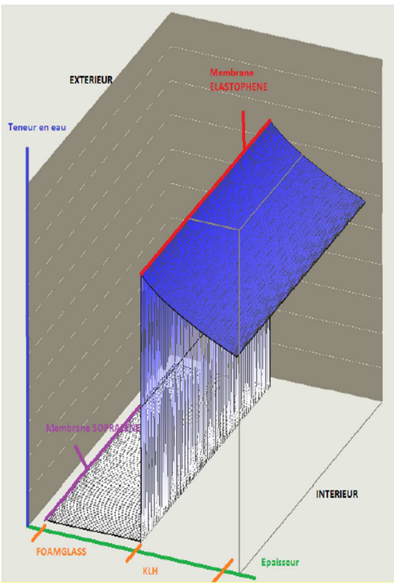
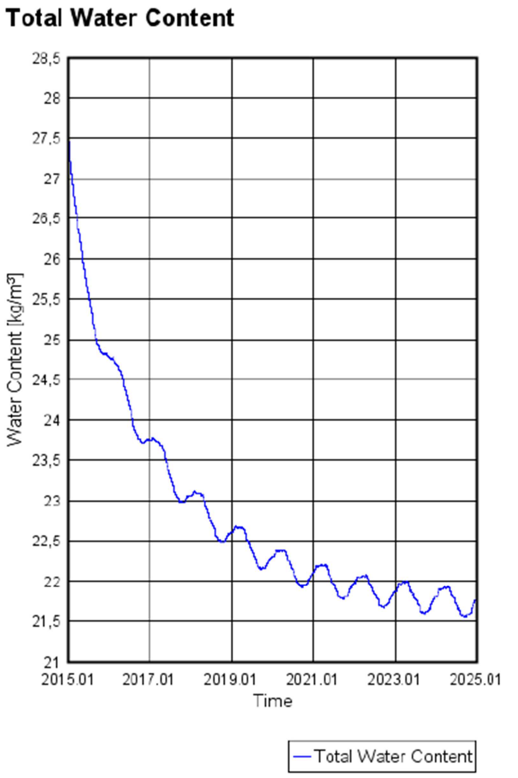


Figure 31: *Water transfer diagram (Wufi analysis) / CSTB document*



6 CONCLUSIONS

This document covers the analysis of the wood-steel accessible roof structure of the air pavilion and particularly the presentation of the assumptions adopted for the roof design. As a general view the uniqueness of this so-called large span structure is not to be a form-finding analysis with the very typical idea to find the best ratio between the volume of material and the span. At the contrary the shape of the surface is simply a consequence of its accessibility as a “promenade”. This situation has led to a very unusual level of complexity regarding the engineering design also maximize by the use of a non-isotropic material such as wood. At the end of the design process the real complexity of the structural system is to be at the same time a roof in a very humid atmosphere and then subjected to skin analysis which might improve the structural design.

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