Hybrid structure for the ArtLab EPFL pavilion

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Abstract

The ArtLab pavilion groups three distinct buildings under one same roof. This project, developed by the Japanese architect Kengo Kuma, winner of the 2012 competition, was built on the EPFL campus, next to the Rolex Learning Center, from 2014 until 2016.

The pavilions, with their unifying roof, create a contrast between traditional slate roofing and contemporary design with their dramatic length and various inclined planes as proposed by the architect. But, this contrast also characterizes the structure: while it is made of simple frames, each of them have a specific geometry which calls for modern construction methods and innovation.

The variable geometries of the frames were generated using a 3D model of the pavilions to guaranty the continuity of the different roof planes. To obtain constant cross-sectional frames, a hybrid structure composed of a wooden frame coupled by two frames made of perforated steel plates was developed. Using non-linear material laws, a numerical model was validated with experimental results of bending tests and then used to design of these hybrid frames.

Finally, the northern roof cantilever was created with a three-dimensional pleated structure made of solid wood. The behaviour of this structure was modelled with shell finite elements and verified on site by monitoring the displacements of the roof during construction.

These pavilions demonstrate that innovation can improve the quality of construction.

Keywords: glued laminated timber, perforated steel plates, hybrid structure, innovation, 3D modelling, experimental study, bending tests, , wooden pavilion

1 Introduction

The ArtLab pavilion unites the three following buildings: the Welkom pavilion with the Montreux Jazz Café; the Data Square which shows the outstanding projects of EPFL (Ecole Polytechnique Fédérale de Lausanne) such as the Human Brain Project; the Art and Science pavilion with temporary expositions of the Gandur art foundation.

The project developed by the Japanese architect Kengo Kuma, winner of the 2012 competition, was carried out by the contractor Marti Construction SA. Structural engineering was performed by INGPHI Ltd.

The unifying roof covers the different pavilions as well as the access road to the underground parking of the Rolex Learning Center and a pedestrian pathway that connects Allée de Savoie with Route des Noyerettes. The pavilions reach an important total length of almost 230 m, as shown on the photomontage of Figure 1, presented during the competition.

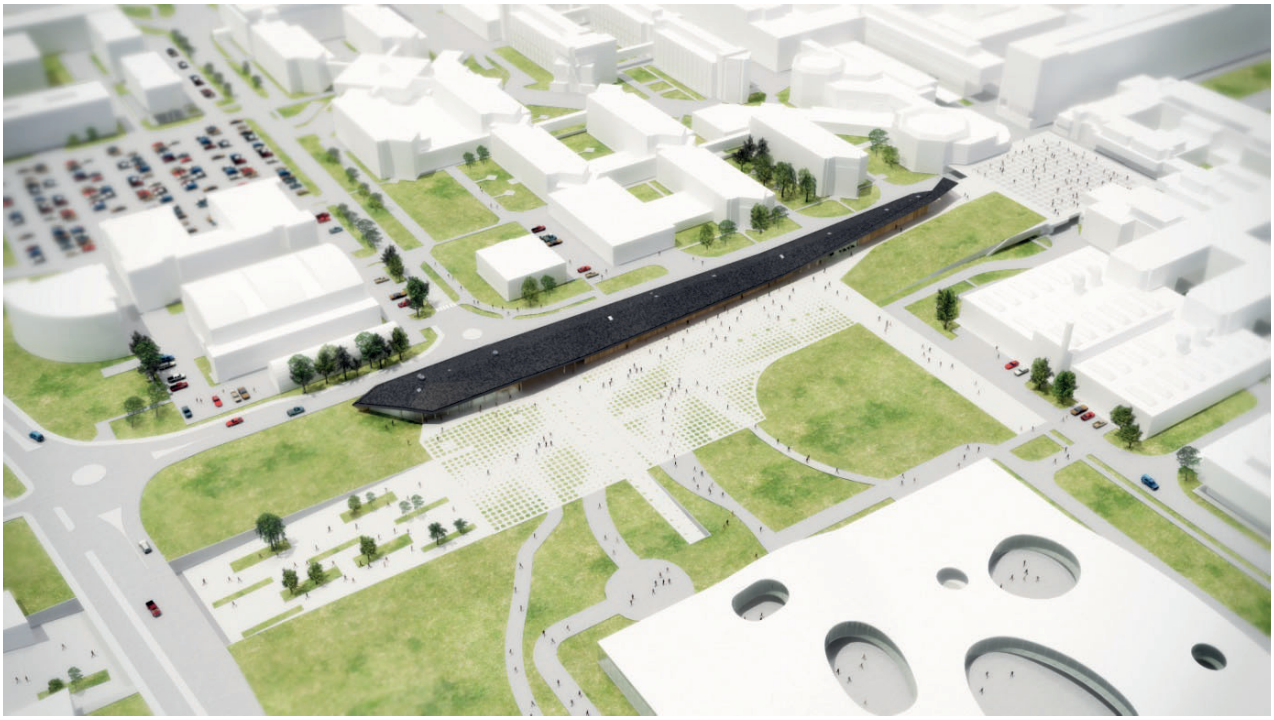

Figure 1: Photomontage of the competition (architect Kengo Kuma)

This roof is covered by black slate sheeting to recall the traditional stone construction methods. It stretches out over such a long distance that it takes a dramatic dimension. This exaggeration creates a contrast between the traditional stone roofs and the modern image which is even more emphasized by the various inclined planes of the roof as proposed by the architect.

This contrast characterizes also the structural design as it is composed of 56 straightforward frames spaced every 3.8 m which have a very specific geometry that calls for modern and innovative construction methods. In fact, all frames have a different shape because of the different inclined roof planes, but also because of the pavilion width which varies between 6 and 16 m, like shown on Figure 2.

This roof superstructure is supported on a basement made of monolithic reinforced concrete construction that consists of a foundation slab and an underground level.

Figure 2: Geometry of both end-frames

2 Frames initially planned in wood-aluminum

As part of the competition, the frame structure has been proposed as a hybrid glued laminated timber (glulam) structure covered by perforated recycled aluminum plates. This solution is interesting for sustainable development, but it could not be realized because of the different material behavior of wood and aluminum. In fact, as summarized in Table 1, the thermal expansion coefficient and the Poisson's ratio of both materials are very different. Moreover, wood has a sensitivity to air humidity which aluminum does not.

Table 1: Material properties for wood and aluminum

Material	Wood (red pine)	Aluminium
Thermal expansion coefficient α	0.4 to 0.5 10^{-5} °C	2.3 to 2.7 10^{-5} °C
Poisson ratio ν	0.45 à 0.46	0.33

This incompatibility problem had not been detected during the competition. At the beginning of the project phase, this issue was demonstrated with normalized delamination tests, according to [1].

The samples were also being submerged in water and submitted to pressure, temperature and humidity variations. These tests showed that the difference in material behavior leads to delamination of the aluminum plate shown on Figure 3, even when using a glued connection or a connection with metallic ergots like.

Figure 3: Delamination of the aluminum plates observed after the tests

This behavior incompatibility as well as delivery problems of the aluminum plates with large dimensions have led to abandon this proposition.

3 Frame design as a hybrid structure

The frames are the main load-carrying elements of the pavilion. They also impact the image of the latter because they are partially visible from the outside as well as from the inside of the buildings. They give rhythm to the pavilions as a unified image is seek.

The concern was to design structural frames with span lengths varying from 6 to 16 m using the same cross-section. The first solution was to design the section for the largest span and to apply this section to all other frames which would then be oversized. This solution was not chosen because the image of the succession of frames became too heavy.

To comply with the proposed architecture, an innovative structural concept has been developed. The aluminum plates have been replaced by steel plates. The frames are made of glued laminated timber coupled on both sides with frames made of perforated steel plates.

The proposed structure thus becomes a hybrid structure in the sense that its behavior is influenced by the behavior of the two structural elements, the wooden frame and the frames made of perforated steel plates.

The advantage of the hybrid structure lies in the total width of the frame section which can be kept constant. It is the thickness of the perforated plates that vary according to the frame span. As the spans gets larger the thickness of the steel plates increases while the thickness of the wood section decreases accordingly.

This idea allows to have a homogenously sized frame. Additionally, the roof and the façade elements, positioned between the frames, all have the same dimension.

The frames covering the exterior passageways are heavily loaded and thus require a hollow steel section with the same cross-section dimensions as the other frames. Unfortunately, they were executed with full steel plates without any perforation.

The pavilions were modeled in 3D to generate the variable geometry of the frames and guaranty the continuity of the various planes in the roof. The model is shown on Figure 4 with the different frame cross-sections.

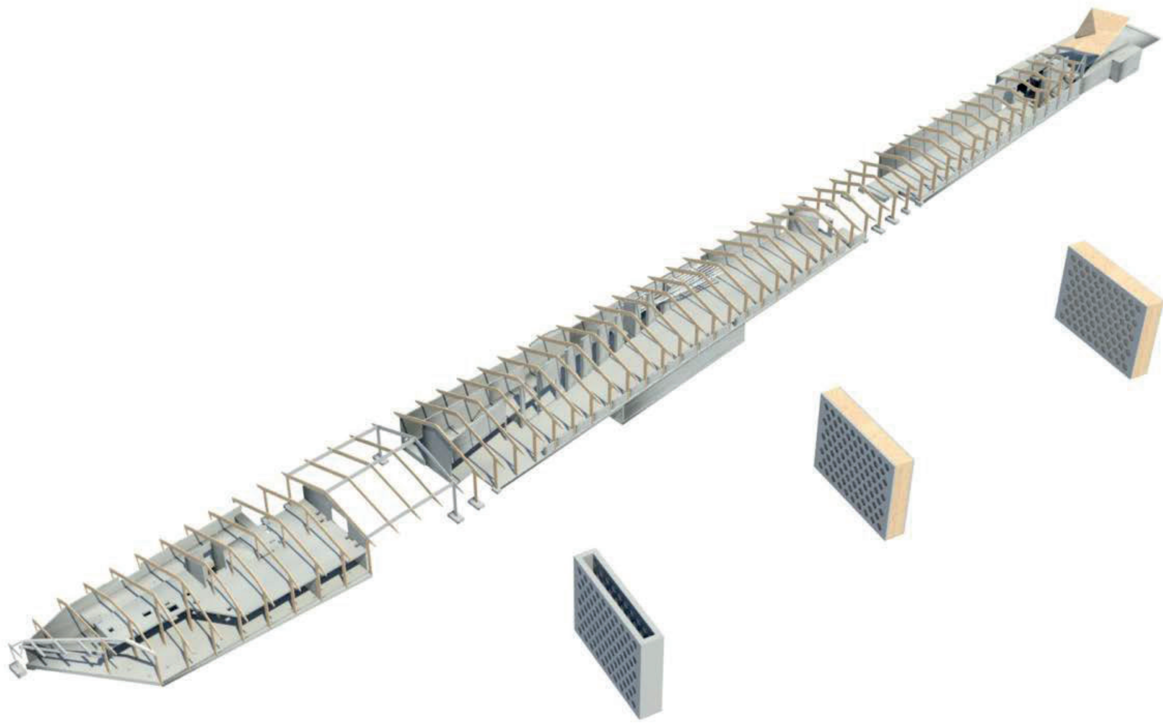

Figure 4: 3D view of the frames

The design of the frames led to the use of a central frame made of glued laminated timber (glulam) of type GL28k. The perforated plates are made of S355 steel with a thickness varying from 3 to 15 mm. The perforations in the plates have 50 mm diameter and are done by oxy-cutting. The connection between wood and steel is ensured by an epoxy resin applied over the full wood surface. The gluing had to be executed with care to allow a uniform distribution of the glue.

The construction of the frame angles, which are heavily loaded, has been simplified with the use of the perforated plates that transfer a large part of the internal forces. The rest of the forces is transferred by drilled threated rods connected to the central part of the wooden frame with epoxy resin.

4 Behavior experiments

This innovative hybrid structure has been tested in the laboratory. First, the delamination tests allow studying the behavior of the interface between the two materials. This led to the addition of steel ergots at the end of the steel plates. Further, bending tests on beams with reduced dimensions, like described in [2] and shown on Figure 5, have been carried out.

Figure 5: photo of the laboratory experiment on a hybrid wooden-steel beam

The load-displacement curves of the different bending tests and the numerical simulations are presented on Figure 6.

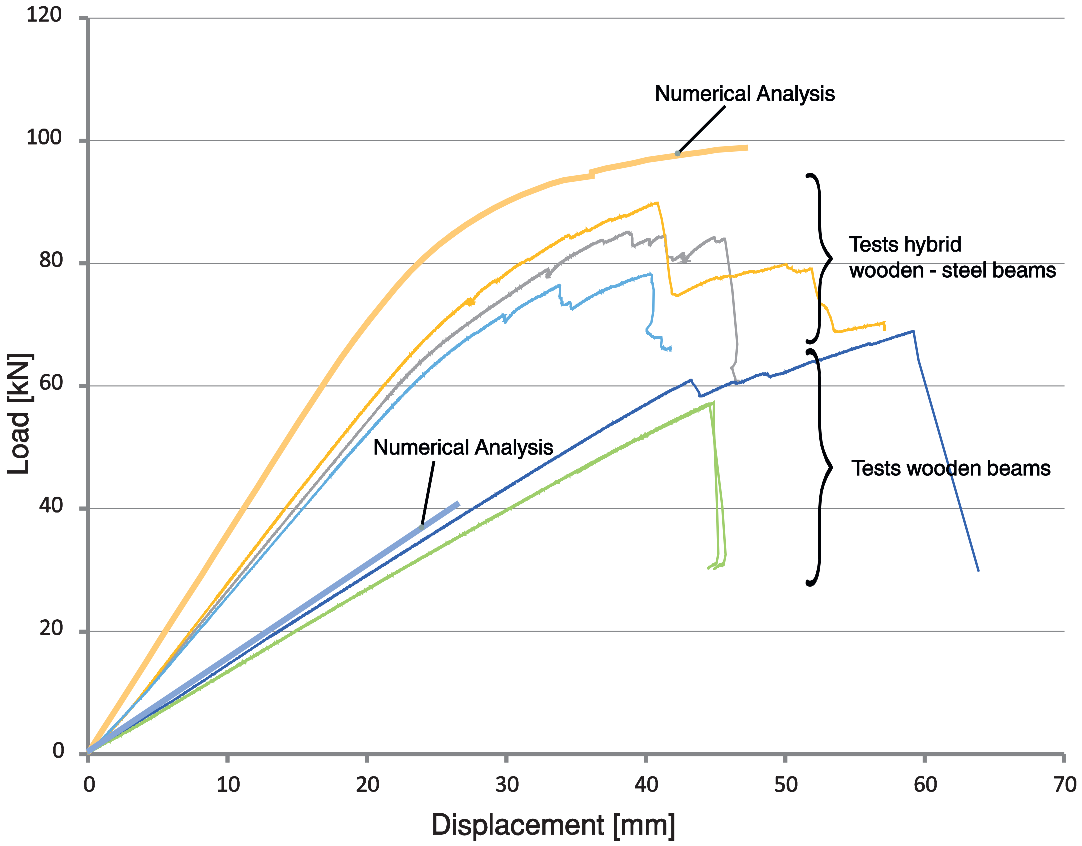

Figure 6: Load-displacement curves of the bending tests

The following points have been observed:

- Coupling perforated steel plates with wood increases the failure load and the rigidity of the beams;
- No delamination between the wood and the steel plate took place before maximal load;
- The hybrid wood-steel structure improves the ductility of the beam behavior;
- The numerical simulations of the hybrid beams overestimated the failure load and the rigidity. To improve the prediction capabilities and so reduce the overestimated stiffness, the flexibility of the epoxy glue interface should be considered in the numerical model.

The tests also confirmed the non-linear behavior of the hybrid wood-steel element which was initially predicted by the numerical simulations.

5 Roof composition and assembling

The composition of the roof is presented on Figure 7. The frames are connected to each other by panels that consist of longitudinal purlins and OSB panels that serves as bracings. The eaves are built with purlins fixed to the frames. Hanging from these are Kerto Q panels covered by OSB panel to achieve a pointed edge.

The whole roof is covered by 1 cm thick slate sheeting. It is placed on top of a wooden roofing battening. To accentuate the huge roof, the rain gutters are integrated in the thickness of the covering.

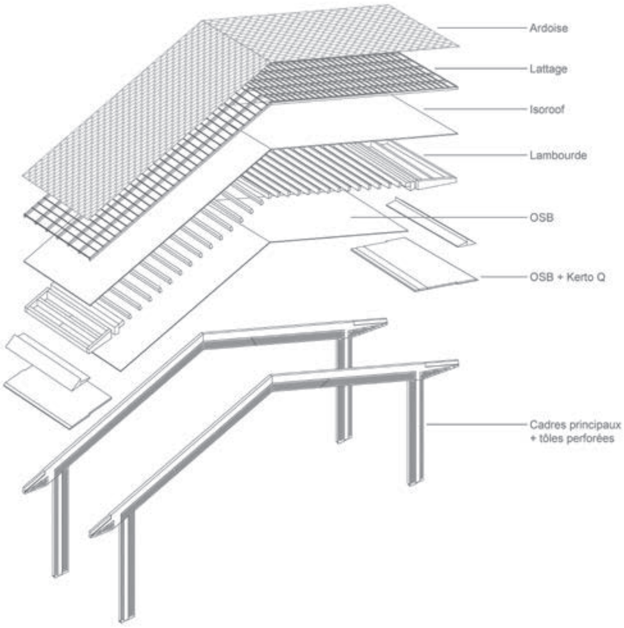

Figure 7: Construction view of the frames and the roof covering

After the construction of the concrete structure, the frames were lifted by crane. Afterwards, the panels of the walls and roof were slid between the frames like shown on Figure 8.

Figure 8: Lifting of the roof

6 Cantilevered northern roof

The northern roof is singular as it covers the main entrance with an asymmetrical cantilevered roof with an angle, a pleated structure. This cantilever extends the roof of the pavilions to which it is linked and has only one support. The link to the pavilions is guaranteed by tension cables and steel profiles as presented on Figure 9. The angled and asymmetrical geometry of the cantilever induces bending, shear and torsional stresses.

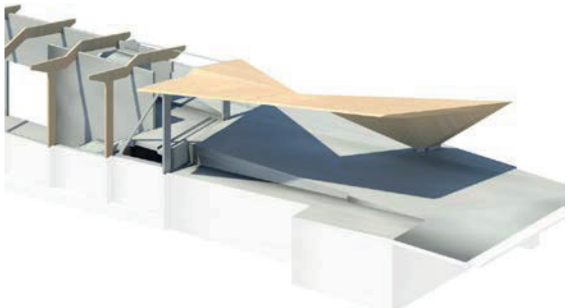

Figure 9: 3D view of the pleated structure of the northern roof in solid wood

The northern roof has been designed like a three-dimensional shell structure made of solid wood reinforced with embedded threated steel rods fixed with epoxy resin. The different parts were fabricated in the workshop and lifted on site with a crane like shown on Figure 10.

Figure 10: Lifting of the northern roof

The behavior of the northern roof has been modelled using shell finite elements. The vertical displacement at the edges of the northern roof was measured during construction. The evolution of these displacements is shown on Figure 11. The different construction stages can be observed in the curve. The displacements stabilized at a value of 20 cm, which corresponds to the values obtained by numerical simulations.

A front view of the finished northern roof is presented on Figure 12.

The whole ArtLab pavilion is shown on Figure 13.

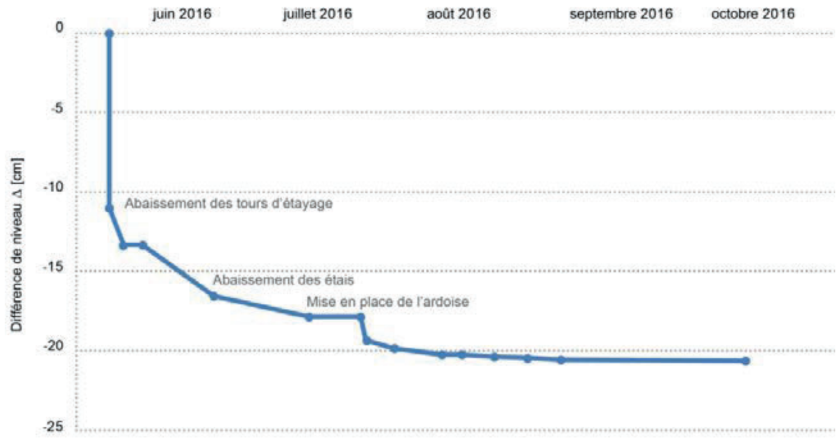

Figure 11: Evolution of the vertical displacement of the end of the cantilevered northern roof

Figure 12: Front view of the northern roof

Figure 13: View of the whole ArtLab pavillion

7 Conclusion

The ArtLab pavilion, with its unifying roof, creates a contrast between traditional slate sheeting roofs and contemporary image with its dramatic length and its various inclined planes as proposed by the architect. This contrast also characterizes the load carrying structure which consists of a succession of simple frames, each of them with a different geometry that calls for modern and even innovative construction methods.

In fact, to generate the variable geometry of the frames, a 3D model of the pavilions was built. This model guaranties the continuity of the various planes in the roof. To realize the frames with constant sections, a hybrid structure composed of a wooden frame and two frames made of perforated steel plates was developed. Considering the non-linear behavior of the two materials, the behavior of the hybrid structure was predicted numerically and correlates the bending test. Finally, the cantilevered northern roof, a pleated structure was designed like a three-dimensional shell structure made of solid wood whose behavior has been modelled using shell finite elements. During construction, its displacement was verified with on-site measurements.

These pavilions demonstrated that innovation can improve the quality of construction.

8 References

[1] NF EN 391 « Bois Lamellé collé – Essai de délamination des joints de collage », 2002.

[2] EPFL-UOR, Essais de flexion sur des poutres mixtes bois-béton ; heig-vd, january 2015.