World Conference on
Timber Engineering
Oslo 2023

WIDE-SPAN LVL ROOF STRUCTURE FOR AN INDOOR SWIMMING POOL

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ABSTRACT: The wide-span roof structure for a new indoor swimming pool in Luxembourg was built as a prefabricated LVL ribbed slab system. The 23.75m span was achieved with PI-elements consisting of slender (75mm) closely spaced and 1100mm deep webs. With the thickness-to-height ratio outside the current standards and a structural behaviour close to the performance limits, the dimensional stability and torsional stiffness of the Kerto Q material was exploited to realise the desired filigree architectural appearance. Given the chloride-laden air of indoor swimming pools, metallic components were limited to a minimum to guarantee a durable and maintenance free structure. The bearing on the reinforced concrete substructure was developed in timber through widely notched supports in the girder webs, exploiting the tension capacity of the cross-layers in the LVL. The webs are connected to the roof plate via hot-dip galvanized dowels to maximise the corrosion resistance. The high and precise degree of prefabrication of the PI-elements in transportable elements enabled a quick and efficient assembly on site.

KEYWORDS: Wide-span, LVL, ribbed slab, dimensional stability, corrosion

1 INTRODUCTION

As part of the redevelopment of a school in Luxembourg City, Cents, the campus was extended to include a sports centre as well as an indoor swimming pool. Embedded in the sloped topography, the school campus designed by Auer Weber Architects, Germany, Stuttgart, creates a new plaza for the local neighbourhood.

Figure 1: Exterior view of swimming hall within the school campus

2 STRUCTURAL SYSTEM

The timber roof structure covers the entire 36mx40m plan dimensions of the swimming hall. The indoor space is partitioned on axis 18’, at roughly two thirds of its width, into the pool and the general facilities area. The structural system of the roof follows this separation and consists of two simply supported spans. Vertical supports for the timber roof are provided (a) on an intermediary steel beam and the concrete core walls on axis 18’ and (b) a concrete ring beam on the outer periphery. The concrete ring beam rests on regularly spaced slender concrete wall elements while the steel beam is supported on the concrete core walls and by additional intermediary steel columns. The lateral stability of the building is achieved through the concrete core and the peripheral concrete wall elements. The top slabs of the timber roof PI-beams are connected to form a diaphragm. On the short span, the roof diaphragm is interrupted to accommodate a skylight.

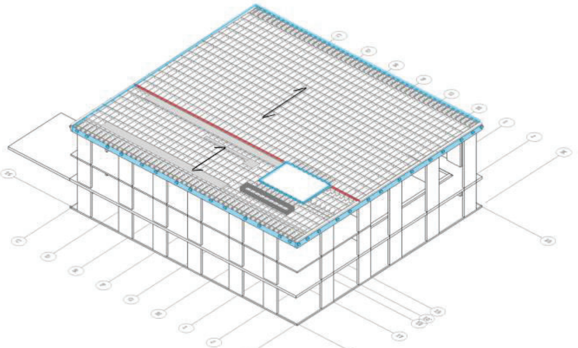

Figure 2: *Axonometry of the indoor swimming hall (blue – concrete ring beam and core, red – steel support)*

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https://doi.org/10.52202/069179-0561

To achieve the architecturally desired uniform and seamless appearance of the entire roof, the structural elements spanning over the two partitions of the swimming hall roof consist of the same type of PI-beams. The height, spacing and thickness of the ribs and plates is kept the same for both spans, although they differ significantly.

Spanning over a free length of 23.75m over the pool area, the prefabricated PI-beams consist of a pair of slim LVL ribs (Kerto Q) at 800mm centres with a height of 1100mm and a thickness of 75 millimetres. The ribs are structurally connected in shear to the top 69mm LVL slab (Kerto Q) by means of hot-dip galvanised steel dowels. The choice for this type of connector was driven by the required corrosion protection, a topic that is further elaborated in section 4 below. The production limits of the LVL Q-plates were exploited to a maximum as the webs and the top slab are both milled from one continuous plate element. The Q-panels were chosen for their high dimensional and torsional stability considering that the thickness-to-height ratio of the webs exceeds current standards. The webs are additionally restrained by 200mm high transverse bulkheads spaced at 140cm centres along the length of the PI-beams.

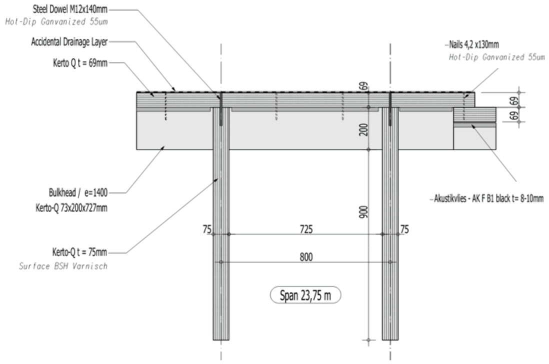

Figure 3: *Section through LVL PI-beams for the 23.75m span*

Figure 4: *Prefabricated PI-beam in the workshop*

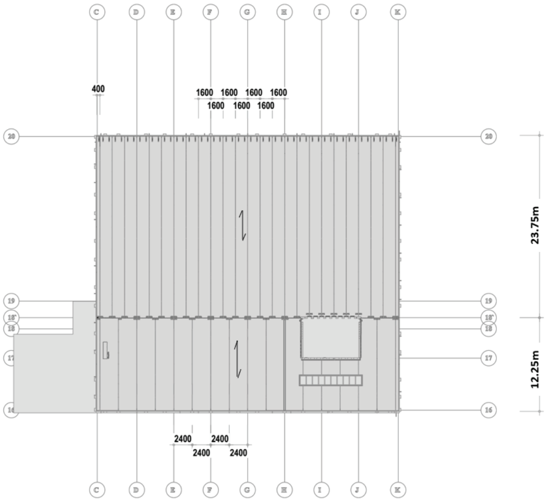

Figure 5: *Plan view of roof*

The LVL ribs are precambered which was achieved via CNC milling of the plates. The precamber was required on the one hand to avoid visual sagging of the beams from the interior view and on the other, to secure the required slope of the roof for drainage. A different precamber was used at the top (180mm) and bottom (120mm) of the ribs.

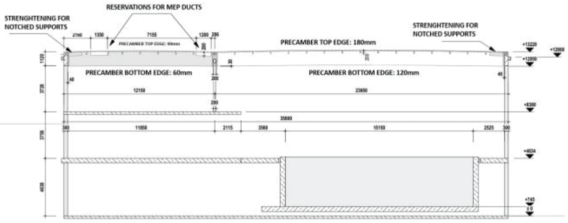

Figure 6: *Section through swimming hall*

The MEP ducts run in the direction of the span so that the number of reservations the roof structure could be kept to a minimum. The lateral distribution of the MEP fixtures was achieved above the general facilities area through reservations made in the smaller span beams at the top of the ribs just below the top plate. An acoustic ceiling with timber lamellas running in the transverse direction closes the space between the ribs. The PI-beams were fully prefabricated in the shop including the accidental drainage layer to allow for a fast and efficient assembly.

https://doi.org/10.52202/069179-0561

3 SPECIAL DETAILS

3.1 SUPPORTS

3.1.1 Introduction

To achieve the desired architectural appearance coupled with the ambition to minimise the use of metallic components, the support of the PI-elements was realised with a deep notch that extends well beyond the usual half-depth limit of the webs. Two main critical points are highlighted in the following figure:

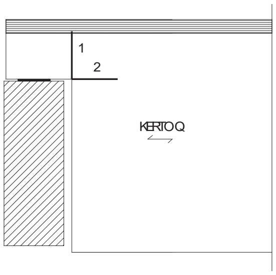

Figure 7: *Support of the single span beam – critical points*

The notches reduce the shear capacity of the beam (1) and raise the risk of tensional failure (2). An alternative solution had been developed by the design engineers.

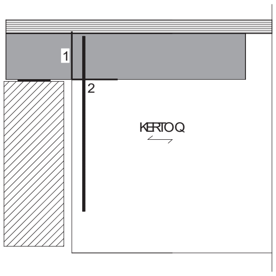

Figure 8: *Thicker beam in upper part (1) and glued in rods (2).*

For this solution, the supports were strengthened on either side of the webs (1) by glued-on LVL plates and strengthened with M14 glued-in rods (2) in the direct vicinity of the support. Additionally, the tensile strength of the cross-layers in the Kerto Q webs was exploited and at the top of the section, the diameter of the glued-in rods was increased via M22/M14 Rampa-sleeves to attain the necessary overall strength.

A verification method of the notch by a reduced shear capacity is given in Eurocode 5 [1].

$$\tau_d = \frac{1.5 \cdot V_d}{h_{notch} \cdot b_{notch}} \leq k_v \cdot f_{v.d} \qquad (1)$$

Whereas k_v represents the reduction factor that considers the geometry of the notch (cf. Formula 6.62 in [1]), the use of formula (1) has to fulfil geometrical parameters according to the Austrian national appendix of Eurocode 5 [3]. The height of the notch has to be bigger than half of the total height of the beam.

$$\frac{h_{notch}}{h_{beam}} \geq 0.5 \qquad (2)$$

In this case, this geometrical requirement is not fulfilled. A finite element model of the entire beam and its support condition has been created to assess the load bearing capacity of the notched support.

3.1.2 Material and methods

One beam with a span of 23.75m has been modelled with the commercial finite element software RFEM 5. The model consists of about 80’000 Triangular surface elements with an edge size of 2.5cm. A detailed stress analysis has been performed on two different models. Model A (MA) consists of a thicker beam in the upper region without glued in rods. Model B (MB) has additionally been reinforced with glued in rods. The linear beam elements of the rods have been connected to the surface elements.

3.1.3 Results

The tension perpendicular to the fibre below the notch is represented in the following table.

Spec.	Reinforcement	σ_y [MPa]
MA	Thicker upper part	4.3 [MPa]
MB	Thicker upper part + rods	2.5 [MPa]

The stress distribution of Model B (MB) is represented in figure 6. The peak vertical stress is located directly below the thicker upper part of the beam. The thickening was pulled down a little on the front side.

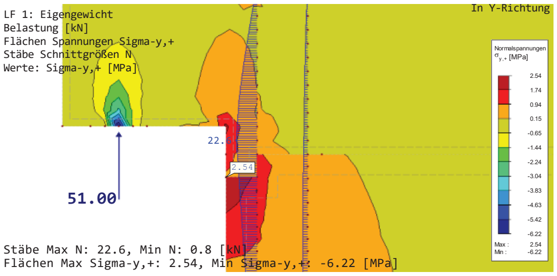

Figure 9: *Traction perpendicular to the fibre σ_y= 2.54 [MPa]*

Due to the higher resistance of Kerto Q, cracking can be prevented.

$$f_{t.90.edge.Rd} = \frac{k_{mod} \cdot f_{t.90.edge.Rk}}{\gamma_M} = 3MPa \qquad (3)$$

Where k_{mod}=0.6 is the reduction factor for permanent loading, $f_{t.90.edge.Rk}$=6 MPa the tensile stress perpendicular to the grain according to the declaration of product of Kerto Q and γ_M=1.2 the material safety factor for LVL timber defined in [1] and [2]. The final solution is presented in the following figure:

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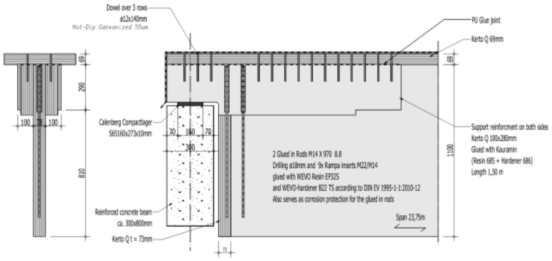

Figure 10: *Final technical solution of the support*

3.1.4 Discussion and conclusion

A detailed stress check was performed for the notched support. The use of Kerto Q reduces the risk of cracking perpendicular to the grain. Additional glued-in bars and thickening of the beams above the bearing area made it possible to solve this geometrically demanding support system. In addition, steel could be avoided. Before such special solutions are worked out, an attempt should be made to achieve direct beam support without notching. However, this is not always possible due to the given boundary conditions.

Figure 11: *Finished notched support of the PI-beams on the concrete ring.*

3.2 PI – Beam

The webs of the PI-girder were statically connected to the slab by steel dowels. The connectors are distributed along the entire beam length and concentrated near the support points (see Figure 12). Without the use of glue, a partially rigid connection is created between the web and the roof panel.

The spring stiffnesses of the anchors can be calculated according to Eurocode 5 [1]. However, they may vary slightly depending on production and tolerances of the holes in the panels. Therefore, the verifications were carried out with half and double spring stiffnesses.

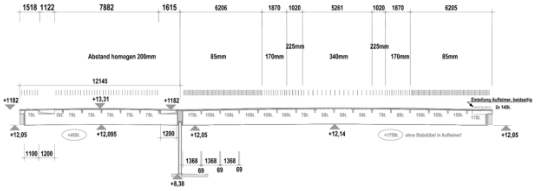

Figure 12: *Arrangement of shear dowels along the beams*

4 CORROSION PROTECTION OF METALLC FASTENERS

A major challenge was the corrosion protection of the metallic fasteners and to get the approval by the local checking authorities.

4.1 SWIMMING POOL ATMOSPHERE

The risk for corrosion of metallic components rises with increasing water vapour in the air. Since the air in an indoor swimming pool is always to some extent humid due to the water evaporation, this environment presents an increased risk for corrosion. Through adequate ventilation and air conditioning measures, a water content of 14g/kg dry air should be an upper bound [5], which for typical indoor pool air temperatures of around 30°C corresponds to approximately 50% relative air humidity. This corresponds to approximately double the amount of humidity present in the atmosphere of typical western European cities. This environment gives rise to a wood equilibrium moisture content between 7-9 M.-% [5] and thus, according to [1], the LVL timber can be classified into the service class 1.

In addition to the air humidity, the presence of salts in the water, in particular chloride salts, contribute to metallic corrosion. The pool is operated with tap water and has a typical average chloride content of around 55mg per litre. Through convection, sodium chloride salts in aerosols are transported through the air and can deposit onto metallic surfaces to amplify the corrosion process. Also, chlorine is usually added to the pool water for disinfection purposes. Free chlorine is typically dosed to a concentration of around 0.3mg per litre and reacts with water to form hydrochloric and hypochlorous acid. The latter, with its high oxidation potential, is the disinfectant active ingredient. Excess chlorine can evaporate as chlorine gas into the ambient air and transform into hydrochloric acid in electrolyte films on metallic surfaces in the presence of water, for example due to condensation.

4.2 CODE REQUIREMENTS

The minimum corrosion protection requirements for metallic fasteners in the Eurocodes [1] is given in Section 4, Table 4.1, reproduced below.

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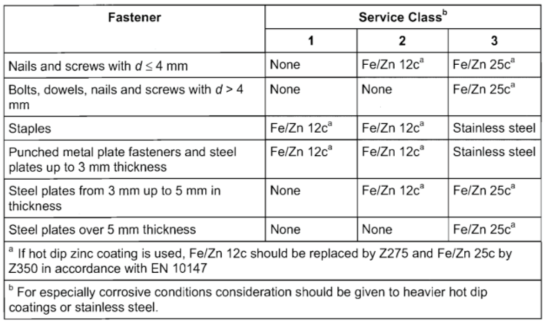
Table 1: *Examples of minimum specifications for material protection against corrosion for fasteners from Table 4.1 in [1]*



Fastener	Service Class[b]		
	1	2	3
Nails and screws with $d \leq 4$ mm	None	Fe/Zn 12c[a]	Fe/Zn 25c[a]
Bolts, dowels, nails and screws with $d > 4$ mm	None	None	Fe/Zn 25c[a]
Staples	Fe/Zn 12c[a]	Fe/Zn 12c[a]	Stainless steel
Punched metal plate fasteners and steel plates up to 3 mm thickness	Fe/Zn 12c[a]	Fe/Zn 12c[a]	Stainless steel
Steel plates from 3 mm up to 5 mm in thickness	None	Fe/Zn 12c[a]	Fe/Zn 25c[a]
Steel plates over 5 mm thickness	None	None	Fe/Zn 25c[a]

[a] If hot dip zinc coating is used, Fe/Zn 12c should be replaced by Z275 and Fe/Zn 25c by Z350 in accordance with EN 10147

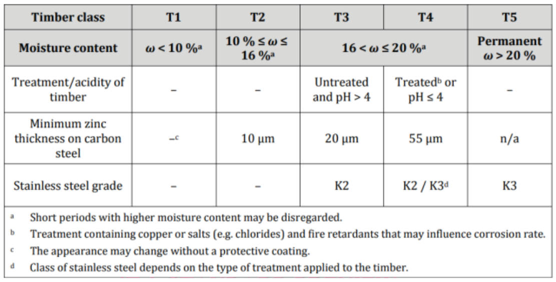
[b] For especially corrosive conditions consideration should be given to heavier hot dip coatings or stainless steel.

It can be seen from this table, that for service class 1, there are no specific corrosion protection requirements for nails, screw, dowels, and steel plates. However, the nature and severity of the corrosive environment and whether the steel is completely exposed to the atmosphere or within and protected by the timber is not addressed.

The German national annexe [2] states in Section 4, that for moderate, severe, or very severe corrosive environments (corrosion categories C3, C4, C5 according to DIN EN ISO 12944-2:1998-07 [7]), the minimum specifications for material protection against corrosion can be taken from the DIN SPEC 1052-100 [4]. In DIN EN ISO 12944-2:1998-07 [7], swimming pools are classified under the category C4 which is a highly corrosive environment. Consequently, according to the DIN SPEC 1052-100 [4] a minimum average zinc coating of 55µm for screws, nails and steel plates is required. Although in the latter document, the corrosive environment is considered, no distinction is made between fasteners directly exposed to the atmosphere and those within and protected by the timber.

This distinction is made in [6], where the minimum requirements for corrosion protection for metallic fasteners in timber as a function of the equilibrium moisture content are given. The relevant table from [6] is reproduced below.

Table 2: *Classes for corrosion resistant materials and zinc coatings for fasteners in the timber — Minimum requirements. Table 1 from [6]*



Timber class	T1	T2	T3	T4	T5
Moisture content	$\omega < 10\,\%$[a]	$10\,\% \leq \omega \leq 16\,\%$[a]	$16 < \omega \leq 20\,\%$[a]		Permanent $\omega > 20\,\%$
Treatment/acidity of timber	–	–	Untreated and pH > 4	Treated[b] or pH ≤ 4	–
Minimum zinc thickness on carbon steel	–[c]	10 µm	20 µm	55 µm	n/a
Stainless steel grade	–	–	K2	K2 / K3[d]	K3

[a] Short periods with higher moisture content may be disregarded.
[b] Treatment containing copper or salts (e.g. chlorides) and fire retardants that may influence corrosion rate.
[c] The appearance may change without a protective coating.
[d] Class of stainless steel depends on the type of treatment applied to the timber.

It can be seen that for an equilibrium moisture content below 10%, no particular protection is required. This is very much in line with the conclusions of the specialist approval [5] that was undertaken for this project. In the latter study, it was concluded that the low concentration of chloride aerosols that get into the atmosphere from the tap water operated swimming pool and deposit onto the timber surface would not pose any considerable corrosion risk for the fasteners embedded in the timber elements. This is to be attributed to the low humidity present in the timber (7-9%) on the one hand, and on the other, the phenolic resin used to glue the veneers in the LVL plates that forms an impenetrable barrier.

5 ASSEMBLY

To ensure a quick erection of the visible timber construction on site, the contractor, Holzbau Amann, decided to preassemble the roof into elements in the workshop. To do so, the maximum width for transportation by truck and the maximum preassembly grade were to be considered.

The initial schedule intended a preassembly for both types of elements, with lengths 12,20m and 23,75m, with a width of 2,40m with each element consisting of 3 LVL ribs. Due to production limitations with the supplier of the LVL boards from Finland it was not possible to manufacture the LVL boards with a thickness of 69mm into 23,75m x 2,40m elements. Hence the roof elements were preassembled with dimensions 23,75m x 1,60m, consisting of 2 LVL webs only.

The fabrication of the roof elements in the contractor's workshop started by milling the LVL beams of 23,75m and 12,20m length on a CNC-machine. On the underside of each beam, the precamber according to the results of the structural analysis was milled. Additionally, on top of each beam the roof pitch was milled by the CNC-machine, giving the roof its final shape.

Figure 13*: Production of the PI-elements in the factory*

The threaded rods for the strengthening of the supports were glued in the LVL beams in the workshop under controlled ambient conditions. Lateral strips of LVL were glued to both sides of the beams to absorb the shear forces near the notched supports.

Furthermore, a protective coating was applied to protect the wood from grime and effects of the weather during transportation and assembly.

https://doi.org/10.52202/069179-0561

After connecting the ribs to the LVL roof boards with hot-dip galvanized steel dowels (55µm), 2 preassembled roof elements were loaded on the truck. Each truck, moving from Southern Germany to the site in Luxembourg, was accompanied by an escort vehicle.

Figure 14*: Two roof elements loaded on the truck*

Arriving on site, the preassembled roof elements, already covered with a sheet acting as a secondary water protection layer, were lifted from the trucks and directly assembled on the concrete structure.

Figure 15*: Delivery via a side street in Luxembourg*

Figure 16*: A prefabricated 23,75m roof element on the crane*

To ensure the assembly of the timber roof without constraint forces, the contractor responsible for the concrete structure had been preliminary advised of the required precision and the admissible tolerances of his works. The concrete works were verified by a surveyor and deviations were to be corrected by the concrete contractor if needed. Thus, the timber roof could be assembled quickly without any difficulties.

Figure 17*: Assembly of the roof with individual LVL PI-Panels*

On one edge of the roof, the LVL beams rest on the concrete ring wall, on the other edge on a fire-proof coated steel profile. Above the steel profile, in between the LVL beams, LVL planks were installed vertically to realize the continuation of the fire barrier.

Figure 18*: Support points*

To protect the wood elements from the weather the waterproofing was installed in parallel to the assembly of the timber roof. Due to the milled pitch on the upper side of the LVL beams, the final roof pitch was in place right away.

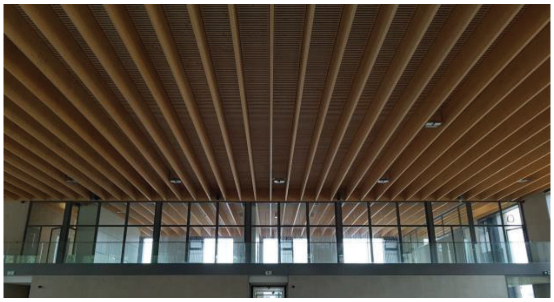


Figure 19*: Finished Roof underside view*

The ensemble of air ducts and cable lines were projected in the design phase. Cutouts and slots in the LVL beams were realized in the workshop, making sure they were placed in structurally stress-free zones of the beams.

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***Figure 20**: Roof underside with acoustic ceiling and LVL-Panels in visual quality*

6 CONCLUSIONS

To meet the architectural requirements and to provide a visually simple and durable structural design, various technical challenges had to be overcome and special solutions had to be developed beyond the limits of the current regulations and standards. The solutions developed exploit the material and size limits of the LVL panels and the details were designed with a minimum of metallic components given the stringent corrosion protection requirements. A high degree of prefabrication allowed for a fast and minimally disruptive assembly on site. The result is a sophisticated ribbed-slab roof structure, milled and assembled in a quality close to joinery.

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