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ENVIRONMENTAL, ECONOMIC AND MOISTURE RELATED ASPECTS OF LARGE SPAN TIMBER STRUCTURES IN HIGHLY CORROSIVE SURROUDINGS

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ABSTRACT: This paper will address the material design strategy of designing a large roof structure in corrosive surroundings like swimming hall facilities. The paper will give an insight into the moisture measurement approach chosen for the wooden parts of the innovative roof construction. Furthermore, the paper will explain the follow up process and on-site moisture-measurements during the building construction phase, revealing the moisture impact on the material and the process of documenting and approving the roof structure after a heavy water leakage during the construction.

KEYWORDS: material design strategy, CLT, moisture management, moisture ingress, corrosive environments

1 – INTRODUCTION

The material choice for swimming facilities is a complex and demanding process. In the finished “Tøyen-bath” in Oslo - Norway, both steel and timber were compared in the early design-phase of the project. The city of Oslo's strong environmental policy emphasizes increased use of timber in public buildings. Comparisons were made regarding both costs and LCA. Early in the construction process, water ingress into the roof construction called for areal moisture monitoring and revealed moisture pockets. Targeted drying measures helped to lower the moisture content below critical levels and kept the construction process on track.

2 – DESIGN PRINCIPLE

2.1 PRELIMINARY DESIGN

The architects aimed to integrate the technical systems of a modern public swimming pool into the roof structure, creating an open and spacious bathing environment. Simultaneously, the design needed to align with the City of Oslo’s strict environmental policy, which promotes increased use of timber in public buildings. This approach resulted in a distinctive egg-carton or Belgian waffle-like aesthetic. Our role was to preserve the architects’ vision and translate their conceptual rendering into a functional structure, ensuring that the final execution closely reflected the initial design (Figure 1).

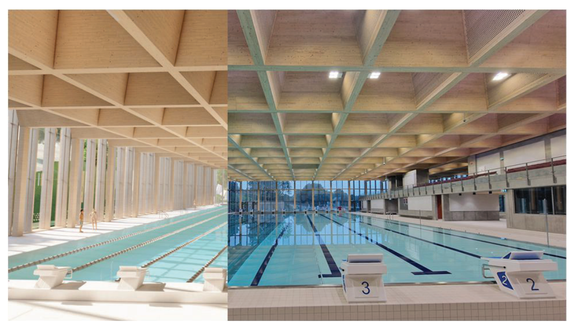

Figure 1: Rendering of the initial design (left) compared to the final result (right).

The roof structure of the new main swimming facility at Tøyen in Oslo is designed as a system of hollow wooden beams, combining cross-laminated timber (CLT) and glued laminated timber. The hollow space within the structure serves as a technical floor, integrating essential building systems. Atop the structure, a green roof collects rainwater, which is repurposed for use in the swimming facility. The inner surfaces of the structure accommodate HVAC and electrical systems, while perforations in the surfaces improve acoustics. Additionally, the shape of the structure optimizes natural light utilization.

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The core design idea was to go beyond a conventional technical floor by making all surfaces an active part of the structural system. Instead of a traditional lattice structure with passive cladding and a separate roof slab, the lattice was essentially "eliminated" and replaced by the visible surfaces and roof slab, which together form a hollow beam.

Several different solutions with glulam trusses were first considered. However, these were discarded since they took up too much space within architectural roof-shape meant for a technical floor. The solution was to utilize the architectural vision and shape of the structure as the main loadbearing structure.

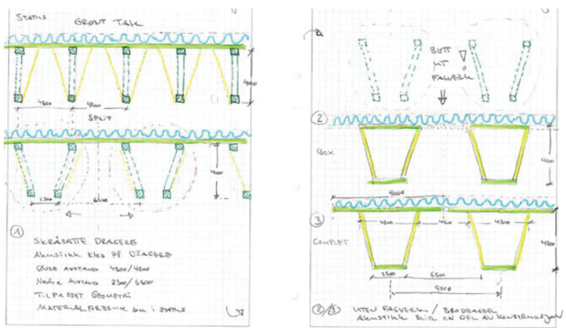

Figure 2: Rendering of the initial design compared to the final result.

The design primarily focused on achieving flexural stiffness, balancing the client's economic demands with the market's production capabilities. A parametric study was conducted to determine the final section. Seven different configurations were assessed based on material usage and stiffness. To facilitate comparison, the values were normalized as illustrated in Figure 3: the lightest section was set at 100% (green line), and the least stiff section was set at 100% (yellow line).

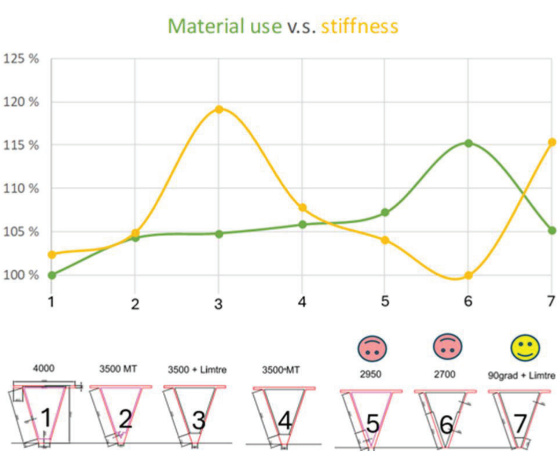

Figure 3: Rendering of the initial design compared to the final result.

This approach not only reduces material usage by minimizing layers, but also ensures that the architectural concept is seamlessly integrated with the structural system.

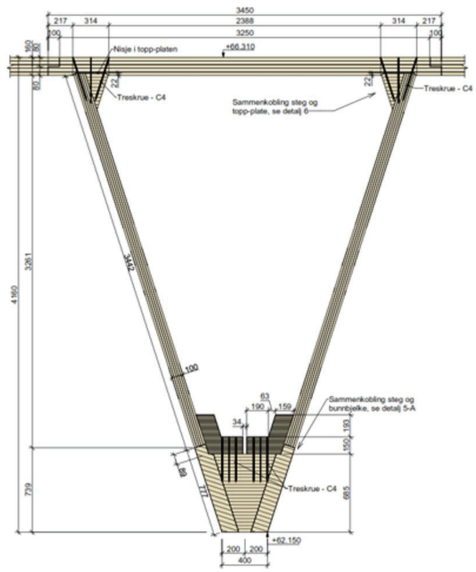

Figure 4: The final section of the construction.

The final roof consists of multiple beam sections spaced at 4.5-meter intervals, completed by a smaller plate between the tops of two beam elements to accommodate tolerances. Perpendicular elements with the same outer geometry are placed every 4.5 meters to support acoustics and two-way load distribution. The acoustic chamber and top plate enhance stiffness by drawing support from adjacent girders, reducing deflection. Steel brackets and tension rods secure the bottom connection, clamping acoustic elements to the girders through friction. This system increases overall rigidity and minimizes deflection along the structure. The final section is shown in Figure 4.

2.2 DESIGNING FOR ENVIRONMENTAL AND ECONOMIC ASPECTS

To ensure that the choice of material would not be a cost-driving factor in the project, a comprehensive analysis was conducted comparing a steel truss roof structure (Alternative B) to the proposed timber solution (Alternative A) for the new Tøyenbadet. The study focused on verifying that the selected material would not significantly increase costs while also examining structural feasibility and environmental impact.

The assessment explored the possibility of using a steel truss system instead of the original mass timber solution. The analysis considered typical elements for cost estimation and did not include coordination with other technical disciplines. The steel truss was designed to maintain the same aesthetic appearance from inside the pool area as the timber alternative by cladding it with 60mm mass timber panels. The load-bearing structure remained consistent with Alternative A, and a corrugated steel deck was chosen for its cost-effectiveness and structural benefits.

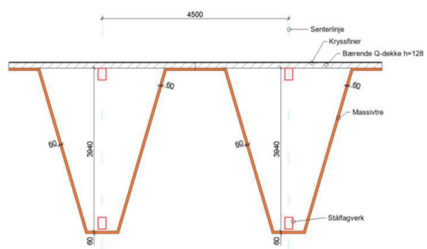

Figure 5: Section a steel truss with CLT claddings as an alternative structural concept.

A detailed cost estimate compared the two alternatives in early stages. The estimated total cost of Alternative B was NOK 35,400,000, while Alternative A was significantly lower at NOK 28,580,000, making the steel solution approximately NOK 6.86 million (24%) more expensive in 2019 currency. The primary cost driver in Alternative B was the need for additional elements such as connection plates, bolts, and high scaffolding for installing the timber cladding. Furthermore, 40% of the costs of the steel truss solution was attributed to non-load-bearing elements necessary to maintain the desired aesthetic.

A life-cycle assessment showed that the steel truss solution would result in significantly higher greenhouse gas emissions. The steel structure was estimated to generate 360.5 tons more CO2-equivalent emissions than the timber solution, an increase of 48%. Since the roof contributes substantially to the building's overall material-related emissions, choosing a steel truss roof would lead to a 20% increase in total emissions for Tøyenbadet. This would undermine the project's environmental goal of reducing material-related emissions by 40% compared to a reference building. Achieving this target with a steel roof would require stricter emissions reductions in other building components, such as concrete.

Despite efforts to optimize costs and structural efficiency, the steel truss alternative remained considerably more expensive and environmentally detrimental compared to the timber solution. The steel option also introduced additional complexities that could lead to further unforeseen costs. Given these findings, and the requirement to maintain the interior aesthetic, it was recommended not to proceed with further development of Alternative B.

3 – DESIGNING FOR MOISTURE

3.1 MOISTURE MANAGEMENT

One of the crucial advantages of constructing with CLT-panels is the rapid assembly of the skeleton of the construction work. A high degree of prefabrication and just-in-time delivery of the components enabled the builders to close the roof of the indoor swimming pool within a couple of weeks. A significant amount of effort was dedicated to developing a construction proposal that was both buildable and met the technical and climatic requirements of the project. Detailed drawings outlining an installation sequence of the structural elements were prepared, ensuring a feasible assembly concept with set levels of acceptable moisture during the different phases.

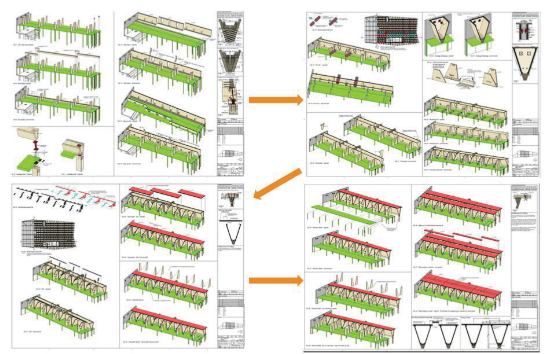

Figure 6: Step by step installation sequence of the structural elements.

In recent years, there has been a strong emphasis on evaluating and ensuring moisture levels in wooden structures. A valuable reference for comparison is "Quality assurance of timber structures" [1] published in Biel 2019. Here different types of buildings, including swimming facilities were evaluated.

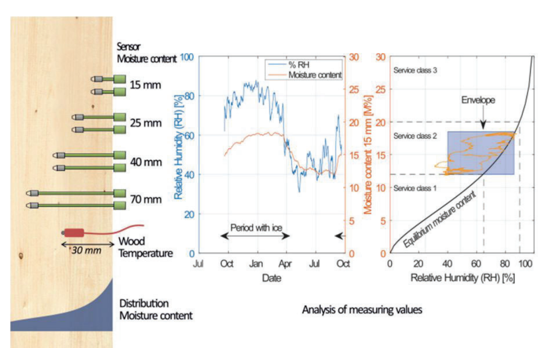

Figure 7: Used source for monitoring concept of moisture level [1]

The target equilibrium moisture content for the timber structure was set at 11.5%, closely aligning with the moisture content at the time of procurement. This was based on an operational temperature of 30°C and a relative humidity of 65%. An exception was identified for the

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uppermost layer of the top plate, where an expected equilibrium moisture content of 14.5% was determined, corresponding to an operational temperature of 29°C and a relative humidity of 73%. Over time, this would result in gradual moisture accumulation in the uppermost layer, stabilizing at the projected levels.

For Tøyenbadet to be built as timber structure, a robust and straightforward approach to moisture management were crucial. The use of cross-laminated timber (CLT) is only permitted in Climate Class 1 and 2, which means that moisture content must remain within specified limits of less then 20 %. The critical equilibrium moisture content in wood is considered to be 15% as this threshold prevents internal moisture transport within the wood. Below this moisture level, the timber effectively shields screws from corrosive air exposure, but the screw will be exposed to corrosion above this value. In addition if the moisture content exceeds 20%, conditions become favorable for decay, mold, and fungal degradation. Hence the core objective is to minimize moisture variations within the wood structure. Maintaining a controlled equilibrium moisture content through the whole section, is a fundamental aspect of maintaining the CLT panels structural integrity as well as risk assessment regarding corrosion impact on fasteners.

A crucial prerequisite for successful moisture control is strict monitoring during the construction phase. As outlined in the initial design discussions and preliminary project sketches, the proposed solution involved a combination of temporary roof structures and a lightweight mobile roofing system. This was discussed and presented to the client during the conceptual design phase and a system for water protection during the construction phase were described in the tender documents.

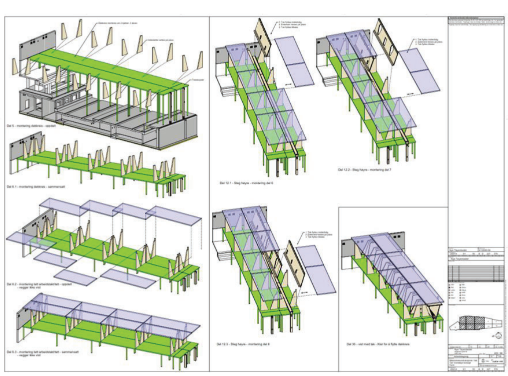

Figure 8: Drawing as part of the initial water protection concept.

Implementing a clear and robust moisture control plan is essential. The key points for such a plan align with Norwegian structural timber execution standard NS 3516 - Appendix A. To further enhance the reliability of the chosen approach, SINTEF, one of Europe's largest independent research institutes, conducted an assessment addressing key aspects of moisture and corrosion protection for the structure. The SINTEF report provided justification for reducing the corrosion protection class of the screws from C5 to C4 since the screws would be fully embedded in the timber and the operational moisture equilibrium would be less than 15 % sbd the would be no moisture transport within the timber.

Furthermore, the initial design proposed that elements would be delivered with a fully adhered asphalt membrane serving as a vapor barrier over the load-bearing structure. This membrane was intended to be installed at the factory, as detailed in the assembly concept included in the tender documents. However, both the contractor and the manufacturing facility stated that the factory installation of the membrane was unfeasible due to fire hazard concerns. Instead, they supplied a self-adhesive rainproof membrane secured to the top plates and additional tarpaulins to cover the exposed bottom elements. The bitumen membrane would then be applied to the temporary protection on site when the elements were placed at their correct location.

3.2 MOISTURE INGRESS DURING CONSTRUCTION

Persistent heavy rainfall significantly impacted the effectiveness of the temporary weather protection during a period of the construction. Despite efforts to dry the surface of the self-adhesive membrane before applying the tape between joints of elements, adhesion issues to the tape arose. In addition primer was not used between the self-adhesive membrane and the asphalt membrane, leading to poor adhesion. This resulted in improper bonding between the membrane and the fabric, allowing air pockets to form. Subsequent rainfall and snowmelt resulted in water infiltration beneath the asphalt membrane, causing the tape securing the weather protection fabric to loosen. This ultimately led to free-flowing water penetration through the construction joints, posing significant challenges to moisture control.

Figure 9: Shows that the bitumen membrane did not bond to the fabric.

The extent of water ingress was mapped by extensive measurements in the 5 layers of lamellae from the upper and lower side of the roof plate. The time required for drying the upper layer was estimated using building physics simulations performed with the WUFI® 2D software based on the average wood moisture content measured at specific locations and in different depths in the CLT roof elements. The moisture gradient across the thickness of the simulated section was interpolated.

The adhesive layer between the individual layers was modeled using the properties of polyurethane (PUR), which is classified as a hard plastic and defined in the software as a non-porous material with a porosity close to zero. This means the bond lines prevent vertical water transport within the roof elements.

Three different drying regimes within a sensible range of temperature control and relative humidity were compared. The simulations suggested the fastest drying of the top layer at an air temperature of 5°C and 50% relative humidity forced through temporary drying tunnels mounted on the top of the roof plate (Fig.10). These measures were implemented and resulted in controlled drying of the roof plate to a large extent. Being able to observe the humidity and control the drying process in critical joints of the roof made it possible to forecast both deformation and stresses to be within safe measures for the building. (Fig.11)

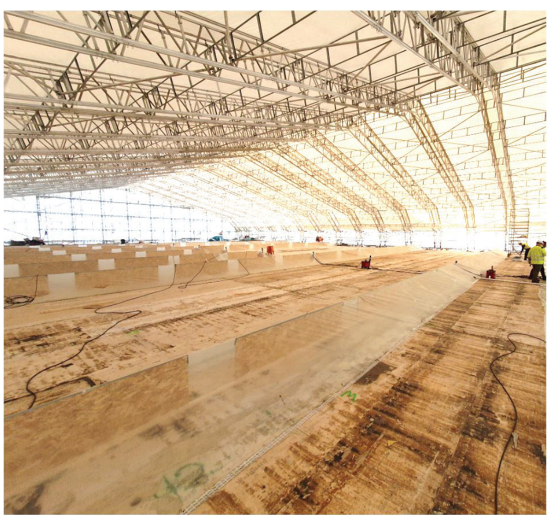

Figure 10: Drying channels along the joints.

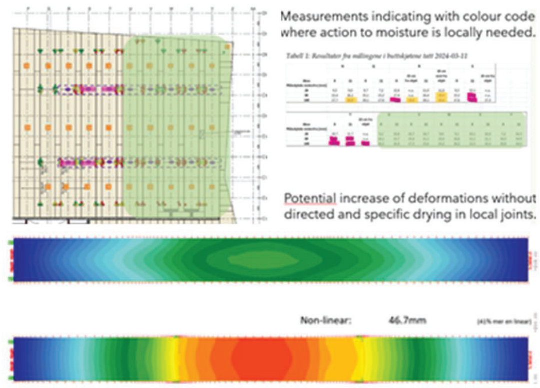

Figure 11: The coordination between measurements and analysis due to the time history of amount and distribution of humidity.

Control measurements revealed some very local wet pockets in the roof plate even months after the drying measures from the upper side of the roof had been terminated. The extent of these pockets in the plane and cross-section of the roof plate was mapped by moisture measurements in a narrow grid to scale forced drying measures to be installed from below the roof plate.

3.3 CONTINUOUS MEASUREMENTS TO ENSURE TARGET MOISTURE CONTENT

An equilibrium moisture content of 12 % is expected in the roof structure during operation of the swimming pool. The drying of the roof plate to this target moisture content as soon as possible is desirable to avoid the risk for mold growth and corrosion of fasteners. With the roof structure closed and watertight from above, drying of the CLT-panels is limited to the lengthy water transport from the cross-section of the CLT panels to the lower surface of the CLT-panels. Permanent moisture logging in different depths in the CLT-panels has been established to allow monitoring and documentation of the drying process (Figure 12). The moisture content in defined depths in the CLT-panels is measured by electrical resistance method and reported to a cloud service where it can be accessed by decision makers and consultants (Figure 13).

Figure 12: Moisture sensors.

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Figure 13: distribution of moisture sensors on the blueprint of the roof (extract from cloud service interface).

4 – MOISTURE IMPACT ON THE MATERIAL

Extensive effort was invested in thoroughly documenting and approving the roof structure after the leakage. Various approaches - including experimental tests, literature reviews, and analytical calculations - were evaluated and implemented. The intrinsic properties of CLT and laminated timber were examined independently, revealing that timber, on its own, exhibits excellent resilience against frost and thaw cycles. In nature, trees undergo the same winter-to-spring transition, experiencing significant fluctuations in moisture without any degradation in capacity.

The monitoring of the structure shows continuous drying of the CLT elements and confirms the effectiveness of the applied drying measures (Figure 14).

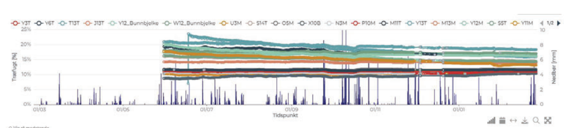

Figure 14: Continuous drying of the roof structure documented by declining moisture content over the last 12 months (screen shot from cloud service interface).

4.1 MOISTURE IMPACT ON SELF-TAPPING SCREWS

Experimental testing was conducted by Rothoblaas to evaluate the withdrawal resistance of fully threaded self-tapping screws used in timber-to-timber connections within CLT structures subjected to significant moisture variations. Two moisture scenarios were investigated: a light weathering condition, where only the top 40 mm lamella was wetted to a moisture content above 30% and a heavy weathering condition, where the entire sample was saturated. Screws of two diameters VGZ EVO Ø7 mm and VGZ EVO Ø9 mm were inserted at a 45° angle using pre-drilled guides, and their tensile withdrawal resistance was measured after a single cycle of wetting and drying to service class one.

Figure 15: Heavy weathering test specimens totally immersed in water.

The results showed that in the light weathering scenario, timber swelling around the connector enhanced the friction, allowing both screw types to retain withdrawal capacities well above the declared TDS values - with VGZ EVO Ø7 mm screws even exhibiting a slight increase in resistance. In contrast, under heavy weathering, the timber's mechanical properties diminished notably, leading to timber failures (for example splitting, Fig. 16) and a significant reduction up to 34% in the characteristic withdrawal resistance for the VGZ EVO Ø9 mm screws.

Figure 16: Test specimens (left), system for testing the withdrawal resistance (middle) and specimens with timber failure (right).

These findings highlight that while the smaller diameter screws are less invasive and maintain a more stable capacity under moisture-induced stress, the overall durability of the connection depends critically on the moisture condition. Hence, these results underscore the importance of accounting for moisture effects and timber variability in the design of CLT connections, especially in environments where prolonged exposure to water is expected.

4.2 MOISTURE IMPACT ON JOINTS AND DEFLECTION

Due to the beam lengths, the CLT elements on the roof are divided both longitudinally and transversely. Transversely, the segments are connected with lap joints that are interlocked together, while butt joints are used in the longitudinally direction. The longest CLT elements in the top panel measure 16 m and are positioned at the beam's center, whereas the end elements are approximately 12 m long for the beams most exposed to moisture, as illustrated in Figure 17.

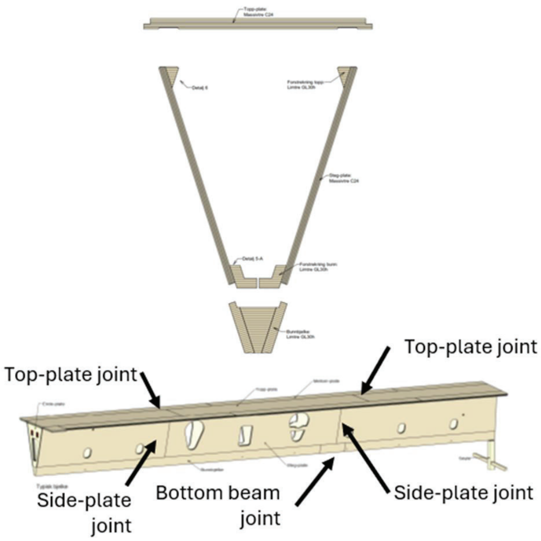

Figure 17: The composed final beam illustrating the division between the elements.

Moisture absorption is particularly evident around certain top-plate butt joints, where substantial portions of the top panel's cross-section became saturated. This localized moisture uptake induces contraction when drying, which in turn increases the deflection of the roof structure. It is conservatively assumed that this contraction forms a hinge at the underside of the bottom beam, allowing free rotation of the beam's cross-section and resulting in an angular displacement between the horizontal plane and the top panel, as illustrated in Figure 18. This effect increases the total deflection of the structure.

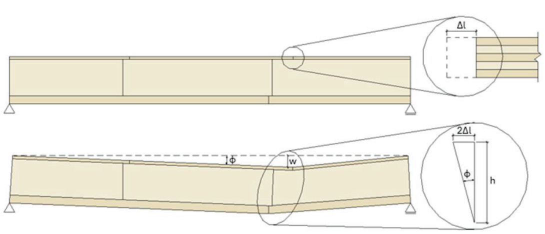

Figure 18: The roof structure beam with an angular displacement between the horizontal plane and the top panel.

The roof structure was constructed on a platform and lowered before all areas were completely dry and before all of the permanent loads were applied. The roof is primarily designed for serviceability - specifically deflection - as the governing limit state, with ample capacity for ultimate failure. However, moisture absorption has softened the top compression joints of the structure, resulting in both irreversible initial deformation and enhanced creep during the first year that exceeded projections.

Monthly measurements with laser scanning provided detailed monitoring of the deflection over time. These measurements reveal a discrepancy between projected and realized deflections, with the maximum deflection occurring away from the center toward regions where the butt joints in the top panel have experienced moisture absorption and subsequent drying (Figure 19). Additionally the measured deflection is slightly larger then the design value. Initially, these differences were more pronounced, but over time the measured deflections have decreased, normalized and converged toward the design projections (Figure 20). The deformation curve exhibits a classical pattern. Under high moisture conditions, long-term deflection develops more rapidly and an increased overall deflection is anticipated.

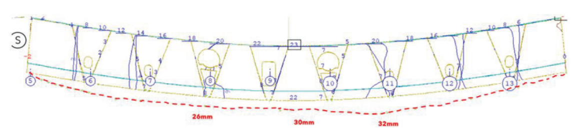

Figure 19: Initial deformation after a few months with the maximum deflection occurring away from the center of the beam.

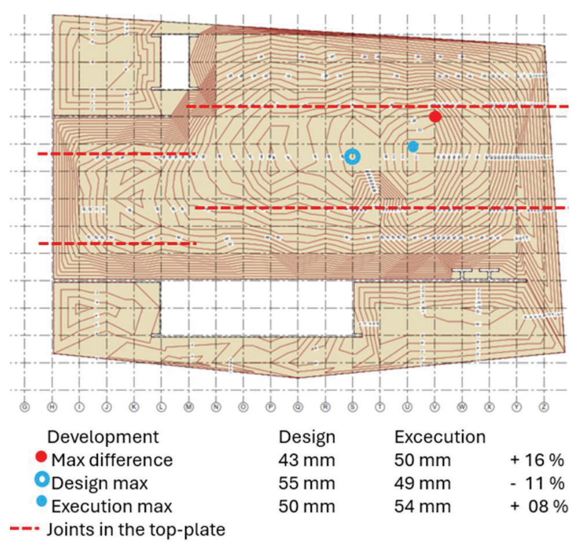

Figure 20: Deformation after a year, converging towards the design projections.

Only minor cracks up to 1.8 mm have been observed in the top panel during inspections although cracks up to approximately 4 mm are not considered structurally significant. No signs of delamination or cracks of a size that would warrant further simulation for capacity reduction have been identified. A procedure for regular monitoring and condition assessment of the roof structure

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has been established. While the roof maintains robust capacity, it has experienced an increase in deflection compared to the design values with a slight lateral displacement of the maximum value relative to the field center. However, the deflection of the roof structure is not visible to the naked eye. The structure is sound, open to the public and is expected to last its lifecycle without further problems.

5 – CONCLUSION

This case study demonstrates that it is possible to build a modern public swimming pool as timber structure, creating an open and spacious bathing environment with the help of a multi-functional roof structure which houses the technical systems, improves the acoustics in the building and allows the optimal utilization of natural light. A comparative analysis with a steel alternative revealed that the timber solution achieved significant cost savings and a reduced environmental footprint, aligning with the city's strict environmental policies. Thus, the use of timber in public buildings was promoted.

All this was made possible through close cooperation between producers, consultants and research institutes which laid the foundation for up-to-date evaluation of the corrosive environment, selection of fasteners and continuous moisture monitoring of the structure. The latter has played an important role in the detection of water ingress into the roof and remedial measures.

Overall, the study confirms that a well-planned timber design not only meets the technical demands of large-span structures in corrosive surroundings, but also advances sustainable construction practices. Importantly, the study demonstrates that even when severe leaks occur, as was the case during construction, there remain effective remedial strategies to ensure that the timber structure remains safe and durable.

6 – REFERENCES

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Figure 21: Final roof strctures open to the public.

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