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BUILDING WITH WOOD STRUCTURES – SUCCESFULL DESIGN PROCESS

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ABSTRACT: Building with wood construction (glulam, CLT, LVL etc.) poses challenges compared to conventional buildings in steel and concrete. Load bearing systems, stability, spans (thickness and vibration of floor elements), connections between structural elements, the behaviour in case of fire and sound insulation properties are the main characteristics that must be addressed individually.

These challenges grow in importance when one desires to display the wood construction as much as possible. The reasons for building with timber are many. To name some: low CO_2-emissions, reduced duration of the building phase, low noise on building site, architectural properties as well as use of prefabricated elements and design processes combining virtual design and construction (VDC) with building information modelling (BIM) that reduces risk and cost compared to on-site building systems.

Planning building projects with normal design phase level of development is in our experience not appropriate to successfully plan and execute building projects with visible timber structures. The reason being that the necessary multidisciplinary aspect of the design is not sufficiently considered.

In this paper we will, through case studies, showcase some of the multidisciplinary design challenges with exposed timber structures and show how a multidisciplinary design process can help to achieve project goals and meet design requirements.

KEYWORDS: Collaboration, Sustainability, building design, structural design, acoustics, fire safety, timber structures, Building information model (BIM), project management, large timber buildings, multidisciplinary engineering, WCTE 2023, Oslo, Norway.

1 INTRODUCTION

Using timber as material for structure in buildings is following an exponential growth in recent years as part of the efforts in reducing CO2-emissions from the construction industry.

To build with timber structures poses more challenges compared to conventional buildings with steel and concrete. These challenges grow in importance with the increasing technical complexity resulting from timber material properties, the number of stories or when one aspires to exhibit the timber construction as much as possible.

Use of modern prefabrications and design processes such as virtual design and construction (VDC) and building information modelling (BIM) are very useful tools, but the design process is also very crucial. Indeed, our experience is that planning massive timber project with normal phase maturity in early project phases will not address properly the engineering challenges posed by larger building projects, especially when some of the massive timber structure is apparent. The main reasons being insufficient multidisciplinary design and level of development.

In this paper we will, through case studies, investigate some of the challenges with exposed timber structures and explain how to achieve project goals and meet design requirements through multidisciplinary design. The case studies focus on CLT and Glulam buildings.

2 SHOWING TIMBER STRUCTURES

2.1 REASONS TO SHOW TIMBER STRUCTURE

There are several reasons for showing timber structures compared to embedding the timber material in other materials such as gypsum boards:

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- Architectural expression: visible wood is growingly sought after as it gives to the architects a new palette of forms, textures, and colours to exploit in their research of building identity and impression.
- CO2-emission: Fewer linings and false ceilings mean less materials and therefore less emissions.
- Reduced costs: Fewer linings and false ceilings lead to less material and less time spent on execution, both contributing to reduce the costs.
- Reduces execution time: As less operations are required, the execution time is consequently reduced.
- Indoor climate: Exposed massive timber helps to regulate the indoor climate with its ability to absorb and release humidity and its thermal insulating properties.
- Psychological effect: This field is currently the topic of research. Strong evidence and conclusions are still to come, but feedbacks from projects indicate that apparent massive timber is generally beneficial for the "feel good" of users. Wood is perceived as a natural material and the presence of natural elements may have positive psychological effect. The physical touch is also felt soft and warm, which may procure a calming effect. Other feedback is that pupils in schools tend to be quieter and calmer in schools with visible wood. Studies of positive effect on patient's recovery in rooms with visible wood constructions are undergoing.

2.2 CHALLENGES

Structure

Timber structures require a different design approach due to the properties of the material compared to other structural materials such as steel and concrete. The design of timber members, such as beams and columns, depend heavily on the design and load capacity of the connections as the connections give the requirements for the associated elements. This means that connection design needs to start early, at the same time as the structural members.

The integrity of visible connections in case of fire loads is also a design requirement that needs to be attended by a structural engineer.

The aesthetic of the connections is an architectural opportunity. However, as showed above, any aesthetic consideration must be part of the connection design right from the start as an input like loads, associated member dimensions and fire safety requirements.

The fact that timber elements and the connections are not standardized gives place to a large degree of innovation. However, new assemblies require in-depth knowledge of wood properties. Advanced calculation and laboratory tests may be needed to reach sufficient confidence and documentation of the solutions.

Fire safety

Fire safety is a crucial aspect for timber buildings. Timber constructions are combustible and as such will contribute to increase the amount of combustible material and hence, the development of the fire.

Height, use and location of the building are determining factors for fire safety requirements imposed by the local legislation.

Fire codes are commonly based on the use of non-flammable materials and approved construction and details providing a known fire resistance. Since timber is a flammable material, the fix fire resistance logic of the fire codes is not directly applicable for apparent timber constructions. The dynamic fire behavior of the load bearing structure in massive timber is therefore established through calculations of the fire energy over time, taking into account both the contribution from the burning structure and the charring insulating effect. This is an iterative process leading to the balance between the amount of exposed timber structure and the required integrity duration for the structure.

The calculated charring layer must be added to the dimensions of the timber elements and solutions for fireproofing the connections must be designed. These two elements are of great influence for the properties and appearance of the bearing structure, proving necessary to integrate fire safety in the early design of any timber construction with exposed timber.

Acoustics

Massive timber has a density around one-fifth of concrete. Sound insulation and impact noise properties of massive timber are therefore quite different from concrete. For instance, for a given thickness, a massive timber element will typically provide sound insulation 15 – 18 dB lower than a concrete element.

As a basic rule, massive timber walls alone do not provide sufficient sound insulation to meet most of the acoustical requirements between rooms. Concerning floors, the combination of limited airborne insulation and high impact noise makes it impossible to have bare elements without any improving construction such as a floating floor and/or a sound insulating ceiling.

The low mass of timber also makes flanking transmission through wall and floor elements an important issue to address. The simplest solution is to use gypsum board linings and ceilings. The flip side is that more operations and material are needed, with their consequences on time, costs, and the environment.

As described above in section 2.1, there are many reasons for showing massive timber structure. The adequate approach to optimizing visible massive timber while taking care of the Acoustics is as follow:

- Use fire safety measures for sound insulation: Fire safety may require non-flammable material in a corridor. Mounting a gypsum board directly on the CLT-wall will barely improve the sound insulation, 1 - 2 dB. Using the same gypsum board as a lining with an air space can improve the sound insulation by 10 or 15 dB.
- Coordinate fire safety measures with sound insulation: Avoid having situations where

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gypsum board is applied on one side of a wall for fire safety reasons and a lining is mounted on the other side because of the sound insulation.

- Use decoupling to reduce flanking transmission: Elastomer strips between wall and floor elements are commonly used for that purpose, but the connections often "short circuit" the elastomer, significantly reducing the effect of the decoupling. Split of floors can also be used, but this measure has important consequences on the load bearing system and the architecture since supplementary beams and columns can be necessary as well as changes of the layout.

Given the important implications of the approach explained above, the acoustical design must absolutely be integrated at an early stage of the design when alternatives for solutions are still there.

Contrary to common expectation, sound absorption properties of massive timber are very low. That means that a building solely made of massive timber will not even get close to fulfilling standard requirements for reverberation time. Additional sound absorbing elements such as false ceiling, free hanging units and wall absorbers are unavoidable.

3 SOLUTIONS

When facing the technical complexity of designing massive timber buildings, it is not uncommon to see architects, builders or property developers asking for a reduction of the requirements.

On a general basis, we do not agree with this approach. For instance, we cannot have less firesafe buildings. Furthermore, people do not want less comfortable buildings than what they are accustomed to. To take an example, electric cars' popularity began the day they became as performant as cars with combustion engine. Likewise, less comfortable timber buildings will lead to reduced buyers' and users' interest.

On the other hand, we believe that better understanding of the material could lead to more harmonized and more adapted requirements for fire safety.

The standard design process is sequential with the architect drawings, then structural design, then fire safety and acoustics. Our experience is that this sequential design is not adapted to massive timber constructions and is the major reason for the perceived added complexity and disappointing results. Changing the design approach rather than the requirements appears then to be the right option.

Based on our experience with successful projects, we strongly believe that early involvement of fire safety and acoustics in the design process and tight coordination between disciplines, especially with structure, are key to success. This approach is explained and exemplified in the paragraphs below.

3.1 DESIGN PROCESS

All building design process goes through different design phases, from the beginning to the end. There are many different definitions and scales of each phase depending on the project size and complexity. Professionals have developed methodologies and tools to handle, standardize and optimize project design processes. In our company Sweco, we do this through our platform *sweco@work* which provides an overview as well as tools and routines for concrete tasks in each phase (Figure 1).

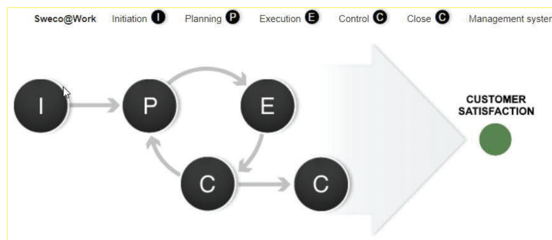

Figure 1: *Sweco@work project planning and execution process overview*

For all project participants, such as decision makers, architects, and consultants, the level of design freedom and influence on project costs evolve during the design and construction process (Figure 2). As the project advances, design changes become increasingly complex and more expensive.

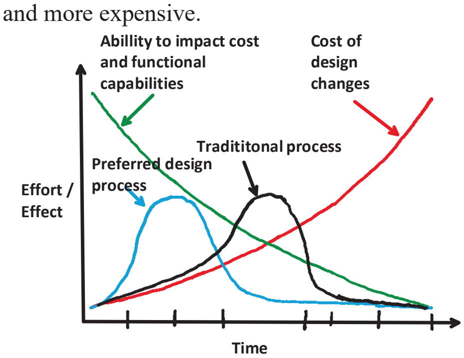

Figure 2*: Illustration of design freedom, cost of changes and design process versus timeline*

Building information modeling, hereafter referred to as "BIM"[1], allows in general building design processes to create digital prototypes during the design process. BIM evolves with increased level of development (or detail) during the design phase.

By sharing BIM during the design process with different disciplines and using design processes like Virtual Design and Construction (VDC)[2] and Integrated Concurrent Engineering (ICE), a greater level of development can be achieved in earlier design phases. This, because design participants share their work before it's finished and by doing so, enables an efficient process where design challenges are identified through a continuous and multidisciplinary process rather than at the end of each deliverable. Design requirements and feedback need to be visualized for all participants to achieve this process. BIM and VDC methodology are preferred tools for that purpose.

Know-how

Timber construction is for many stakeholders new and the skills and experience in the design teams may vary more than in common building constructions.

An example of this is found in structural engineering. The most common design criteria for the cross section of beams and columns with steel and concrete construction is the moment and shear forces in each member. For timber construction, it is the member connections design that most of the time govern the type of cross section to use.

The same type of alternative engineering is found in fire safety and acoustics as well as the design management and the building team. Without the knowledge of timber properties and of the know-how of building techniques with timber construction, there is a great risk of not achieving the project goals.

4 CASE STUDIES

The projects below showcase some of the multi-disciplinary design challenges and solutions with exposed timber structures.

4.1 SCHOOOL AND KINDERGARTEN

Biri elementary school and kindergarten

Biri elementary school and kindergarten is under construction and is expected to be completed in January 2024. The buildings are erected right by the existing high school. The elementary school is approx. 6 150 m^2 and consists of two stories plus technical room on the roof. The kindergarten is approx. 2 220 m^2 over one story with technical room on the roof.

Figure 5. *Biri elementary school and kindergarten. Illustration courtesy* of *JAF arkitekskontor AS.*

The kindergarten is formed as a circle to best adopt to the existing forest around the building site. The roof had originally a fixed inclination from one end to the other in the schematic design model. In the detail project this inclination, together with the circular form, gave some challenges for production of the prefabricated elements and on building site. The level of development in the schematic design phase could in this case had been prolonged in time and resources to better address these challenges before the detail design process. The solution was to have a fixed level between each load bearing axis and to level up the roof from one load bearing axis to the next.

Both buildings are designed with timber construction in the form of CLT slabs and CLT walls and glulam beams. The roof of the kindergarten is built with CLT elements while the school has prefabricated light weight roof elements.

The load bearing system for the elementary school was changed in the detail design phase. These last-minute changes resulted in more steel beams than in the earlier phase of the project. Further glulam beams had to be changed to steel beams to make space (free height) for the ventilation ducts in the detail phase.

Figure 8. *Biri elementary school – Atrium. Picture by Sweco*

To maintain the progress on building site and to meet the delivery deadline, the design of the CLT elements went through a cross disciplinary engineering process early in the detail phase so that all the necessary detailing could be transferred into the production model. The production model was built by the CLT manufacturer based on the structural BIM model. The production model was then verified by the structural engineer before the production of CLT elements started.

Plan drawings of visible side of CLT elements were established early on based on input from fire engineer and acoustic demands.

4.2 HEALTCARE

Frøya healthcare center and nursing home

Frøya is a project that consists of two buildings, one healthcare center and one nursing home, together approx. 8 800 m^2. The healthcare center is a traditionally prefabricated hollow-core concrete element and steel building while the nursing home is mainly a timber construction. The two buildings are connected with a bridge between them for easy access between the buildings.

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Figure 7: *Frøya healthcare center and nursing home. Illustration courtesy of Link Architects.*

The project had ambitious environmental goals. Hence, the use of timber construction together with solar panels on the roof that make the buildings self-sufficient with energy.

The load bearing system for the roof in both buildings consists of prefabricated wood trusses. The timber building consists mainly of CLT panels for walls and slabs. In more open areas, the load bearing system consists of steel beams (HSQ) and glulam columns. Steel beams are used mainly to achieve better access and space for the ventilation ducts going through the building. The exterior walls are built as light frame stud walls.

The stability of the timber building relies on CLT shear walls and CLT shear slabs to withstand the high wind loads in this area located on the Norwegian coastline.

The patients of the center have neuropsychological deficiencies and are often confused. They have limited capacity to escape by themselves during a fire incident. The fire strategy is based on a fire resistance R60 for the load bearing system. The CLT slabs in the ceiling up to the roof are designed for R60 because of low load bearing resistance in case of burning roof trusses. The buildings are fully sprinklered and every CLT wall in resident rooms facing the corridor (and escape route) has EI60 demands.

Sound insulation between resident rooms and between resident rooms and corridors is solved with CLT slabs with concrete topping floating on insulation.

The design team on this project had variable experience with timber buildings. Some had little and some had very long experience. Those with less experience had to learn and/or adapt to the following elements:

- Communicate early multidisciplinary challenges with use of timber and CLT.
- Multidisciplinary design to make sure all the necessary cuts, splits and holes are in the production model of CLT-elements.
- How to achieve and document sound and fire demands with timber solution
- How to achieve rational load bearing solution with ventilation ducts and pipes trough the building.
- Produce a plan of which side of the CLT elements can be visible and which side needs to have a gypsum board lining.

4.3 OFFICE BUILDINGS

Lumber Bygg 4

Lumber Bygg 4 is a massive timber building with a commercial area at the ground floor and office area from the first to fifth floor to be delivered in April 2023. The brief includes BREEAM-NOR 2016 certification, and the ambition was to have as much visible massive timber as possible.

The project started with a multidisciplinary design/build phase with involvement of fire safety and acoustics at each meeting. Hence, every aspect of the different load bearing system alternatives was covered simultaneously. This resulted in an efficient design process and robust principal solutions minimizing changes to be made in the detailed phase.

Figure 3: *Illustration courtesy of VEF Entreprenør AS*

The chosen load bearing system is based on glulam columns and beams. The floors are a hybrid type with CLT combined with concrete slab, both components are mechanically connected. Hence, a larger span was possible, and the number of columns was reduced which led to beneficial consequences for the overall construction layout and the construction costs.

This hybrid solution is also interesting for the point of view of acoustics. Thanks to the good sound insulation properties, it was not necessary to add a floating floor and/or a false ceiling to meet the sound insulation requirements vertically and solve the flanking transmission horizontally.

Strict requirements for reverberation time would normally lead to a sound absorbing false ceiling over the whole office areas. The fire safety engineer has, however, established that an area of around 350 m^2 could be in exposed massive timber in each story. Visible elements in massive timber are the glulam columns and beams as well as part of the CLT-slab underneath. In order to keep that area in visible timber, a great deal of the façade was use for sound absorption using large area of wood wool board instead of wood paneling on the inside of the outer walls.

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The fire proofing of the floor required the use of gypsum boards while the acoustics required the addition of a layer of mineral wool and ceiling tiles underneath. Efforts were put to simplify this construction and showed that the gypsum boards could be replaced with a specific type of mineral wool with sufficient thickness. The sound absorptive properties of the product were investigated and proved to be adequate. Fire safety and sound absorption were then combined in this simple solution consisting in a 70 mm mineral wool layer with wood wool ceiling tiles for the finishing aspect.

Close cooperation between the structural engineer and the acoustician was established right at the beginning of the design when different floor construction alternatives were investigated. It resulted in a cost-efficient construction allowing great flexibility for the fit-out layout with a great deal of visible massive timber. Further on, in the design phase, the cooperation between the fire safety engineer and the acoustician led to a reduction of the costs for the ceilings.

Fredrik Selmers vei 5 (Pilar)

The project Pilar consists of renovating and extending an existing concrete and steel building from 1937 and building a new timber building above the existing building.

The new building is planned to have ten stories, approx. 18 000 m² and to house commercial activities such as offices and café, and/or restaurants. The project is in the schematic design phase when this article is written. The project has ambitious environmental goals and aims to be certified BREEAM NOR Excellent and Paris Proof.

Figure 4: *Fredrik Selmers vei (Pilar) Illustration courtesy of Grape Architects*

The load bearing system consists of glulam timber columns and beams. The two internal stairs and elevator shafts consist of cast-in-place concrete that maintain horizontal stability together with steel and glulam bracing in the facade. The superstructure works therefore as a hybrid structure with concrete, steel, and timber elements.

The building and the floor plans are being planned for future flexibility within a defined technical grid that corresponds to the structural grid.

Local regulation limits the building's overall height and thereby also the height of each story. From the very beginning of the project, this issue is addressed by having coordination between structural engineers, MEP engineers, the builder and the architects. The result of this is that the glulam beam system includes cantilevers to make room for MEP installations. This solution reduces the floor height and also allows to expose beams below the ceiling in most areas.

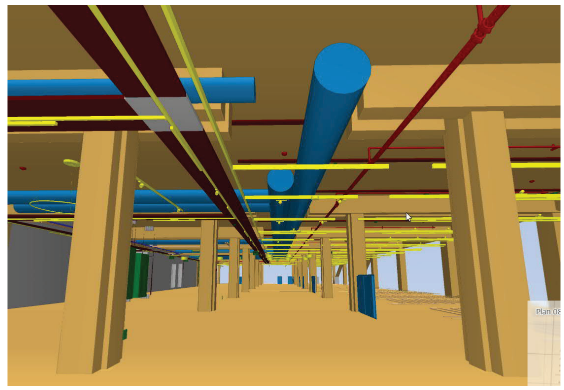

Figure 5: *Cantilever beams designed to reduce floor height due to ventilation ducts.*

Another example of analysis is the calculation of the real fire development curves considering how the fire would evolve rather than to use the pre-accepted fire development curves. The goal being to reduce the timber cross-sections, hence creating more free space between the glulam columns for the technical grids.

The project uses BIM, VDC and ICE sessions to plan and coordinate the design. An example of the visual plan used during the ICE-sessions is shown in Figure 6. By having by-weekly ICE-sessions with work meetings and activities in between, the design participants can plan, share design, coordinate, and provide design information as required to reach the project milestones. The process also measures the completed activities on schedules and keeps track of reasons why activities were not completed as planned.

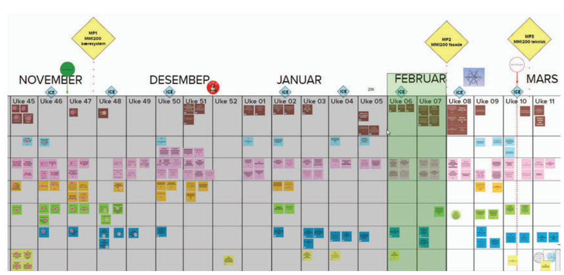

***Figure 6**: Visual planning*

One of the first milestones in the planning was for the structural design to achieve a level of development (LOD) of 200. That meant that the sections and members for all the structure had to be designed from very early on. By doing this, the entire cross-disciplinary team of architects,

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builder and consultants got an early idea of the required dimensions and the challenges this posed.

The design process also includes an iteration of the amount of visible timber with the first goal to visually expose all timber columns. The number of beams is still under consideration due to space requirements. However, by addressing this issue at this early phase the project can handle the challenges and design the building accordingly.

The whole design team consists of consultants with experience with timber buildings.

5 DISCUSSION

In the following section we highlight some of our findings from the case studies we've presented in this paper and experience with other projects.

Level of development vs. timeline
The *Macleamy curve[3]* is in our experience a good visualization of a preferred process where the effort of design and the level of development LOD[4] is higher in earlier phases as to highlight and solve more issues and reach goals early. By having a high LOD in the early phases, more project risks can be identified and addressed, and changes and optimizations are much easier to implement. This requires building owners and the project managers to involve all the consultants from an early stage and thus invest more in engineering work in early phases.

Timber buildings have always a certain level of complexity, which means that the costs associated with changes made late in the design process will contribute to making the technical and economic consequences even greater. That implies that timber buildings must be designed as such from the beginning. Adapting a concrete and steel building to a timber construction in the detail design phase cannot be done without restarting the design process from the beginning.

Objectives related to timber structures should be set as early as possible and eventually adjusted along the way if needed. A common example of this is the amount and location of visible timber surfaces. Answering this means choosing the type of structures with a strong involvement of fire safety and acoustics to find solutions that meet requirements and are cost-efficient. Having a BIM with a sufficient level of development helps to visualize these design intentions early on.

Timber elements are prefabricated and assembled on site. All the design aspects affecting the elements must therefore be coordinated in advance of manufacturing to achieve time efficient assembly on site.

Adaptation of design management
It is important for project design managers and contractors unfamiliar with timber design process to establish an understanding of the different challenges that timber construction poses, to acknowledge that goals related to visible timber needs to be set early and to establish good processes to solve the details.

Timber buildings often require a larger design team as specialists in timber are hired in supplement to a general design team. The larger team results in more interfaces to coordinate, making the need for efficient coordinating tools and methodology even more important.

Efficient design methods
By frequently sharing preliminary design by means of ICE and VDC processes, the discipline challenges are solved along the way between milestones and deliverables. This is key to achieve an efficient multidisciplinary process. By sharing work-in-progress, more design issues are being addressed and participants have more time to solve them compared to processes that are more linear and top-down.

Design culture
Communication with digital platforms that keeps record of changes together with BIM-software support the multidisciplinary design process. However, these are just tools and add little value if not combined with participants that have the know-how to solve the issues, not just from their own discipline's perspective, but also in incorporating other disciplines' requirements and issues. Indeed, technical issues with timber buildings are very seldom solved adequately when disciplines work independently but rather solved by a multidisciplinary team. delivering one integrated solution that often solves multiple requirements. This is especially important when solving issues related to visible timber structure.

Communication
Solving the multiple issues related to visible timber requires to communicate during early stages of the design process. This communication should be directly between architects, design consultants and specialists. In our cases, the most successful projects had consultants that communicated horizontally and solved issues together first, and then presented solutions to the rest of the team and design management.

Knowledge and experience
In our successful cases, project consultants had experience with timber construction, also often combined with a positive attitude towards problem solving, innovation and applying or improving solutions from previous projects.

Proactive participation from the specialist consultants as fire safety engineer and acoustician is essential as their requirements define a frame for the possible solutions.

No need to compromise
It's worth mentioning that in all the above case studies, no compromises were made on the technical requirements, not even on the acoustics although the Norwegian regulation is quite strict in that field.

The costs had also to be equivalent to a standard construction. Hence, the owners' aim of affordable, environmentally friendly, functional, and esthetical buildings were fulfilled.

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6 CONCLUSION

In this paper, we showcased some of the multidisciplinary design challenges with exposed timber structures and explained through case studies how a multidisciplinary design process can help to achieve project goals and meet design requirements. Other essential key factors are design effort in early phase, consultants with experience in massive timber, and efficient design management tools.

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