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Reaching New Heights in Timber-Hybrid Design: Designing the Netherlands' Tallest Timber-Hybrid Residential Building

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Abstract HAUT, a residential tower, is a prototype for building innovative and environmentally-friendly high-rise timber structures. The team – Arup, Team V Architecture, Lingotto and JP van Eesteren – designed and built an ambitious sustainable building: a timber skyscraper, with 21 floors one of the tallest timber hybrid towers in the world. Never before has this highest sustainability rating - BREEAM Outstanding - been awarded to a residential building in the Netherlands. As a result of the new techniques for a timber hybrid tower of 73 meters high, there is interest from all over the world for this combination of sustainability and urban densification.

Keywords Timber, Timber hybrid, High rise, High rise timber, Skyscraper, Plyscraper, Sustainability, Circularity, Amsterdam, Netherlands, Arup

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1. Introduction

Standing 21 floors tall, HAUT is one of the tallest timber-hybrid buildings in the world. The name of the building is a play on the Dutch words for timber (hout), on the French word for high (haute), and on 'haute couture', befitting this 'high end' building in Amstelkwartier – a new district on the edge of Amsterdam's city centre. When the city's municipality launched a design competition in 2016 for the building plot adjacent to the Amstel river, they emphasised the importance of the design being both sustainable and of high architectural quality. Together



Figure 1. HAUT pushes the boundaries of what is possible with high-rise timber design © Jannes Linders.

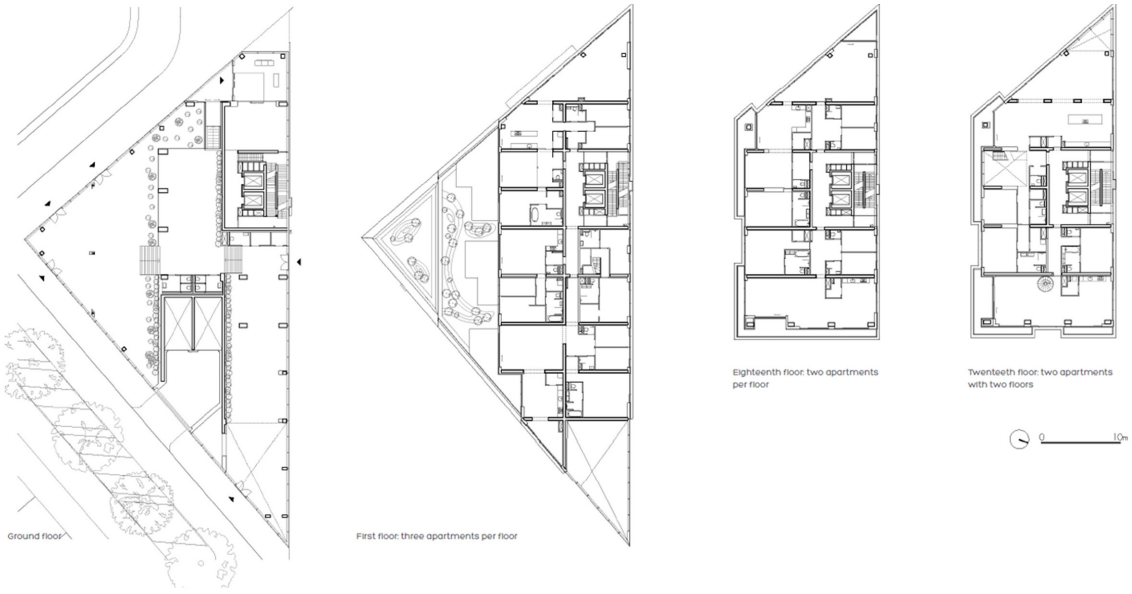


Figure 2. HAUT floor plans © Team V.

with developer Lingotto and Team V Architecture, Arup's multi-disciplined approach has delivered on that intent with a revolutionary timber-hybrid residential tower, reaching an impressive 73m above the river. To engineer this bio-based high rise 14,500m2 residential building, the firm's team of specialists delivered the sustainable, structural and technical design, including building physics, building services, acoustics and fire safety engineering. (Fig. 1,2)

2. Carbon reduction

To achieve its climate goals, the Netherlands has committed to becoming carbon neutral by 2050. Using timber as a building material is one of the most effective ways of accelerating decarbonisation, as the associated carbon footprint is much lower compared to construction with concrete or steel. In addition, the timber acts as carbon storage for decades to come and is a regenerative material. In 2021, more than 80 Dutch companies signed a Green Deal covenant, 'Houtbouw of the Metropoolregio Amsterdam'. With this covenant, Amsterdam is committing to the goal of building at least one in five residential buildings using timber as the main structural material, from 2025 onwards.

Bio-based building is gaining momentum all over the world, as more and more people embrace the natural qualities of timber. While the natural material's enhanced atmospheric, acoustic and health qualities are a factor, the most important driver for the growing use of timber is the potential to significantly reduce carbon emissions. In HAUT, more than 2,800m3 of timber was used in the structure alone, bringing the total reduction in embodied carbon to half of a conventional high-rise structure. When including sequestration, some 1,800 tonnes of CO_2 is stored in the structure (Fig. 3).



Figure 3. More than 2,800 m^3 of timber is used in the structure © Jannes Linders.

3. Sustainable and innovative

In recent years, Arup has designed and delivered a number of timber and concrete/timber hybrid framed buildings, including the seven-storey H7 timber-hybrid building in Münster in Germany, Sydney's Macquarie University Incubator and adjacent four-storey Ainsworth Building, and 80 M, the first mass-timber overbuild in Washington DC. The firm was able to tap into its global experience for HAUT, in particular on the fire engineering aspects, where integrated fire safety provisions played a key part in enabling the overall sustainable timber design.

The architectural aim was for the tower to have a transparent appearance, with lots of sunlight supplying the building with natural heating and optimal lighting conditions. The team designed a façade that consists largely of (triple) glass, with custom photovoltaics (PV) panels that were fully integrated into the façade attached to non-combustible panels and with fire stops at floor levels.

Combined with the rooftop panels, the 1,250m^2 of PV provides an energy-positive exterior that generates a large portion of the building's electricity. The tower features an aquifer thermal energy storage system, sensor-controlled installations and low temperature underfloor heating, making it one of the most climate-friendly high-rise residential buildings in Europe. A rooftop garden and nest boxes for birds and bats add to the biodiversity on site, with the rainwater collected at roof level used to irrigate the garden.

For the residents of HAUT, the timber ceilings create a warm and special atmosphere in the apartments with lots of glass in the facade. And a major advantage of timber construction is also that it allows a high level of customization to create tailor-made 'haute architecture'. CLT panels are easy to customize and offered first time

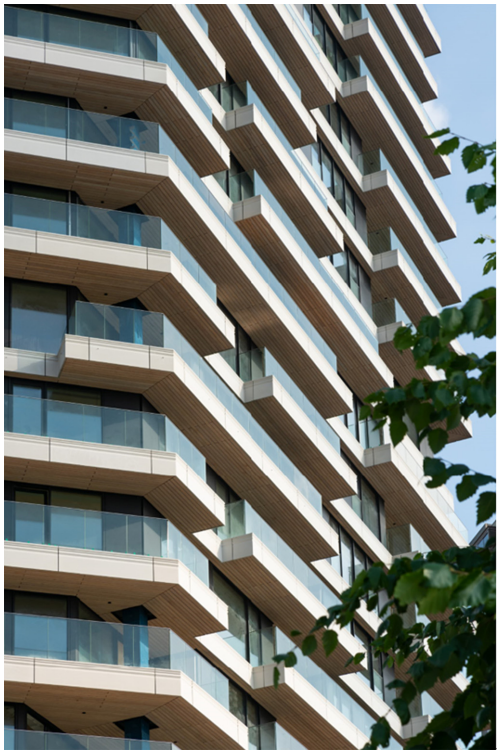


Figure 5. HAUT facades © Jannes Linders.



Figure 4. HAUT is a certified BREEAM Outstanding building © Jannes Linders.



Figure 6. HAUT interior © Jannes Linders.

buyers a choice in their apartment size, number of floors, layout and placement of double heights, loggias and balconies. Unlike most timber buildings, only the interior walls of HAUT are load-bearing, allowing for large floor-to-ceiling windows in the facade. The irregular pattern of balconies and the pronounced, double-height spaces with a panoramic view of the Amstel make HAUT's architecture strikingly distinctive. The integration of almost invisible PV panels in the facade is of high quality.

Many of the specific challenges required innovative solutions. The prevention of noise pollution (creaking, neighbors walking) could be combated by applying a layer of concrete to the timber floors. This immediately helped to increase the stability of HAUT (Fig. 4-6).

4. Structural scheme

With 21 levels, HAUT needed to be easily constructed while satisfying structural, acoustic and fire safety requirements. The design had to consider various site constraints, including the plot orientation, proximity to the river embankment, railway and existing buried data cabling, and the soft soil conditions. The foundations included 104 ground-displacing steel screw grout injection ('Tubex') piles and 54 tension anchors. In addition, a load-bearing diaphragm wall was utilised along the edge of the building plot.

The design principle for HAUT was to use timber where possible, and concrete and steel only when necessary. While the foundations, two-level basement, core, and ground and first floor were constructed in concrete, for the 20 levels above that, timber was predominantly used. Looking for ways to maximise the use of timber as much as technically possible, Arup developed an innovative and affordable technical solution for the upper levels. The result was a custom-designed precast timber-concrete composite floor plate developed in close collaboration with Lingotto, Team V Architecture, contractor J.P. van Eesteren and the German timber specialist Brüninghoff (Fig. 7).

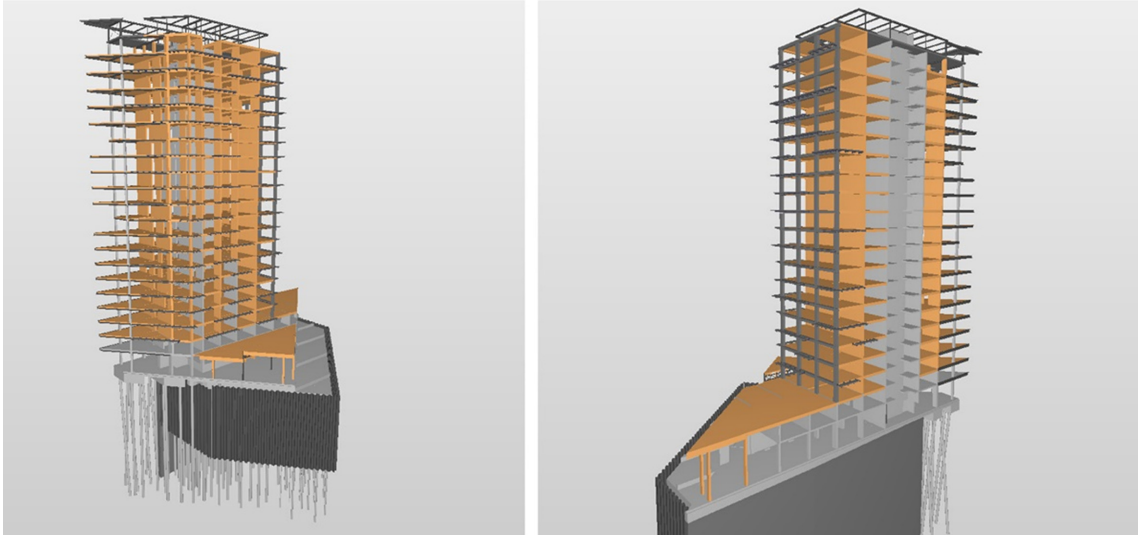


Figure 7. The design principle for HAUT was to use timber where possible, and concrete and steel only where necessary © Arup.

5. Hybrid construction

The floor build-up consists of a 160mm deep cross-laminated timber (CLT) plate with an 80mm concrete top layer, supported on CLT load-bearing walls and glued laminated (glulam) timber columns. In this floor build-up, the two horizontal layers act as a hybrid system, in which the timber takes tension forces and the concrete takes the compression. In certain areas, where the floor edges are not supported by a load-bearing wall, glulam downstand beams were introduced. These beams transfer façade and balcony loads, and provide additional stiffness to the floor. They also double as a tension ring around the perimeter of the floor, transferring diaphragm forces and acting as a structural tie.

The choice of a hybrid floor plate had big advantages for footfall performance (reducing vibration), acoustic performance, construction sequence and detailing. Due to the low self-weight of the floor plates, delivery vehicles could also be loaded more efficiently, resulting in fewer deliveries to the building site (Fig. 8,9).

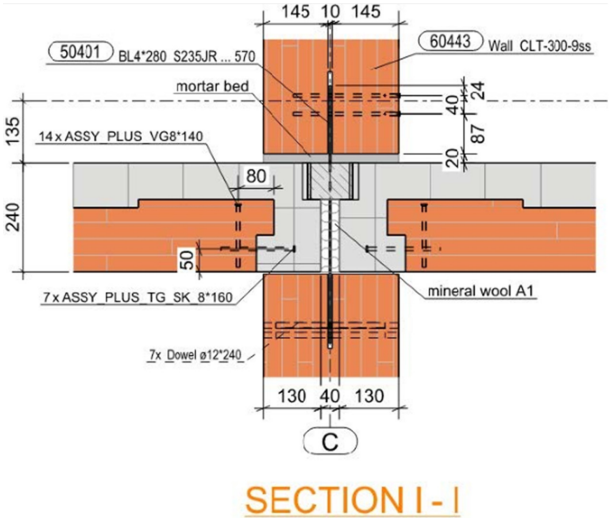


Figure 9. The two horizontal layers in the floor act as a hybrid system with the timber taking the tension forces and concrete taking the compression © Bruninghoff.

6. Stability system

A concrete-timber lateral stability system was used, consisting of a concrete core and two full-height CLT shear walls. The eccentric positioning of the core (for architectural reasons) introduced torsional effects under wind loads, increasing lateral deflections and wind-

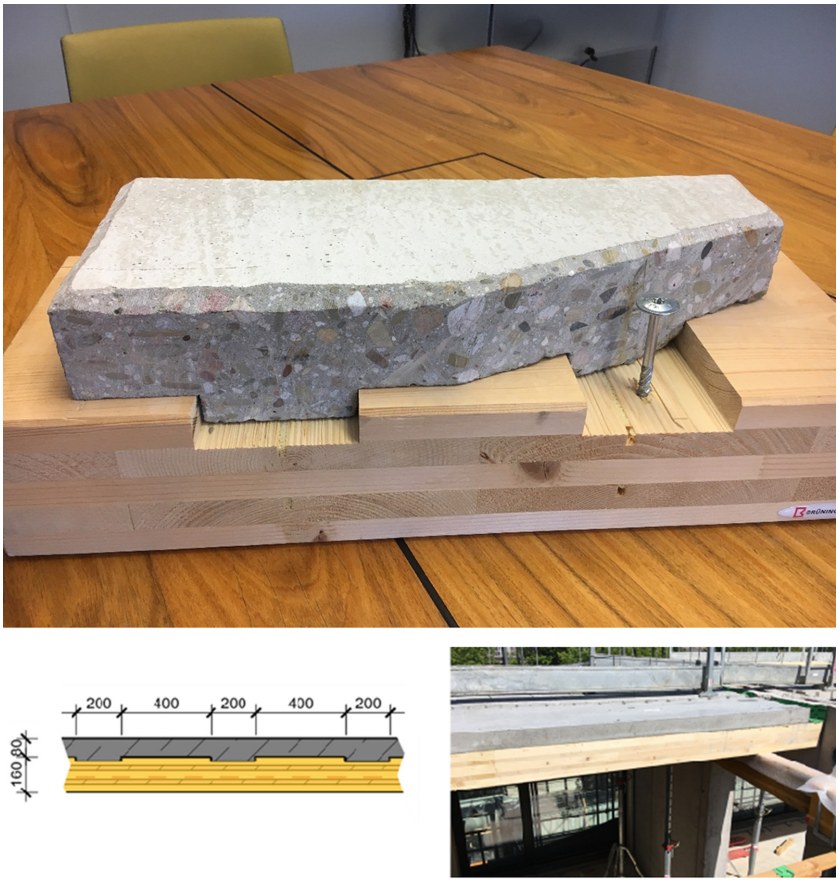


Figure 8. The floor build-up consists of a 160 mm-deep CLT plate with an 80 mm concrete top layer © J.P. van Eesteren.

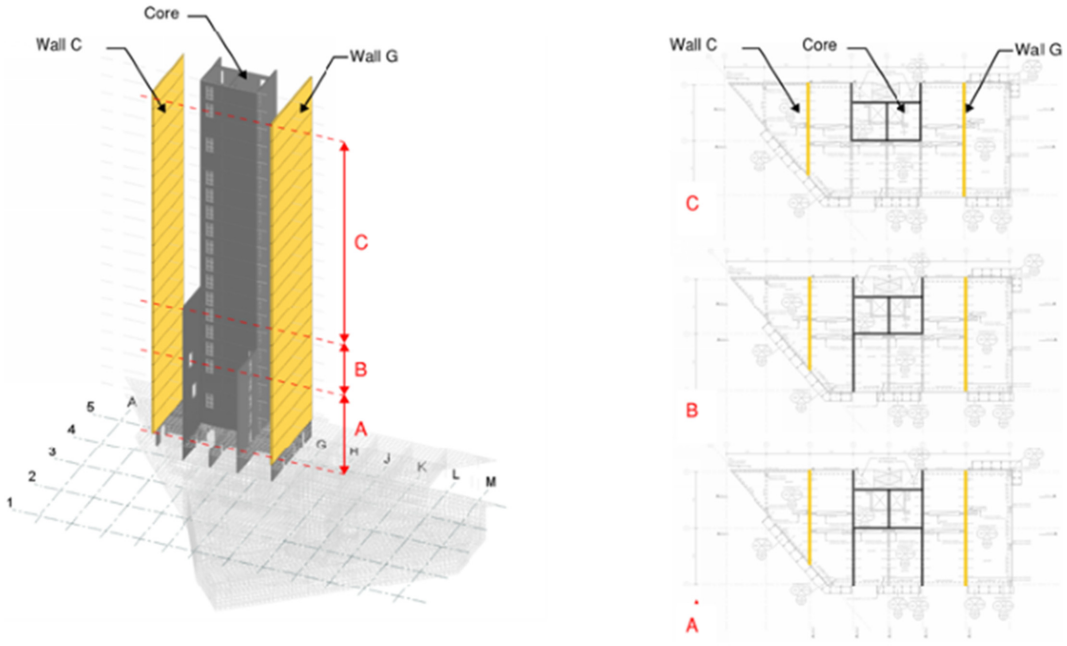


Figure 10. A concrete-timber lateral stability system was used with a concrete core and two full-height CLT shear walls © Arup.

induced vibrations. To determine the expected maximum lateral deflections and perform sensitivity studies, two finite element models were created. The first was a 3D model of the entire lateral load-bearing system, including the concrete ground floor, basement and foundations elements. This was predominantly used as a means of assessing total deflections and the sensitivity to stiffness of individual structural elements, including the foundations.

The second model consisted of a 2D model of the CLT wall, including specific wall openings, orthotropic material behaviour and locally reduced stiffness to allow for acoustical decoupling and connection details. The model was subjected to gravity loads and lateral loads taken from the 3D model. Subsequently, the resulting deflection in the 2D model was compared to the deflection in the 3D one, allowing for a check of the initially assumed stiffness.

The concrete core is also used as a fire brigade entrance and provides the fire escape routes. Risers were used for the building services, which were then distributed horizontally at a high level into each apartment. The distribution of the services required careful coordination to meet the structural, acoustic and fire safety requirements. In the apartments, the air ducting system was distributed in the ceiling zone in the non-living spaces, e.g. corridor, kitchen and bathroom zones (Fig. 10).

7. Vibration control

As HAUT's hybrid structure is a lot lighter than an equivalent concrete building, wind-induced vibrations were considered a risk, and were investigated in detail to ensure compliance with the code. To calculate the expected maximum accelerations, a modal analysis was performed on the previously developed 3D model of the structure.

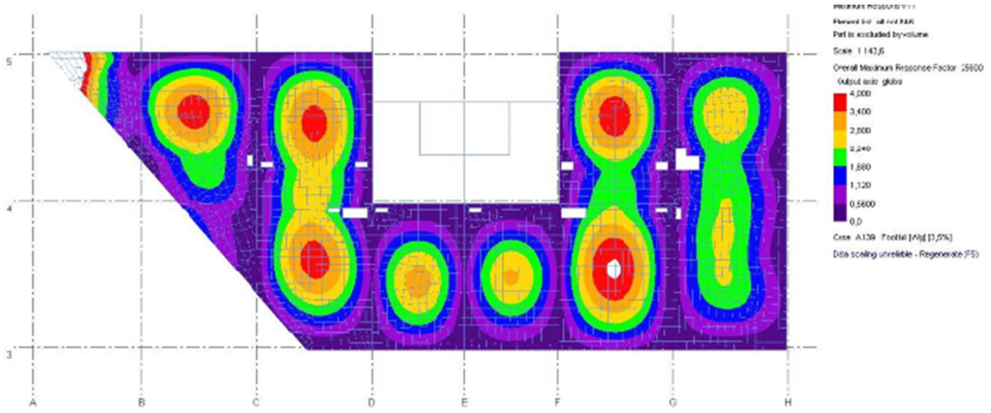


Figure 11. The choice of a hybrid floor plate had big advantages for footfall performance by reducing vibration © Arup.



Figure 12. Glulam perimeter beams provide additional stiffness to the floor and act as a structural tie © Arup.

The calculated vibrations were sensitive to the mass of the building. This was one of the most important motivations for choosing the specific floor build-up that is used in HAUT.

The additional mass of timber-hybrid floor (compared with a full CLT plate) provides additional benefits, improving acoustic performance, reducing footfall-induced vibrations, and increasing performance against wind-induced vibrations. Several floor elements are supported by the concrete core wall on one side, and a timber wall or beam on the other. The difference in mechanical properties between these supporting elements will cause differential movements between the two, and careful design considerations were given to ensure this would not create architectural or functional issues. To take into account creep and shrinkage effects, the concrete core was constructed using in situ concrete, rather than assembled from prefabricated concrete elements.

A wind tunnel test of a physical model of the building was carried out, along with on-site testing during construction with building-mounted sensors. The analysis and results from the sensors on site compared favourably (Fig. 11-14).

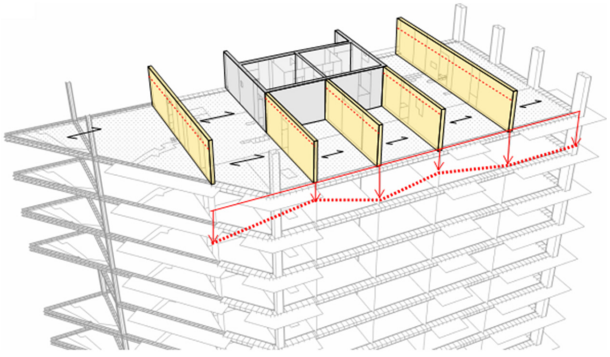


Figure 13. The difference in mechanical properties between the supporting concrete and timber elements causes differential movements and careful design considerations ensured this would not create functional issues © Arup.

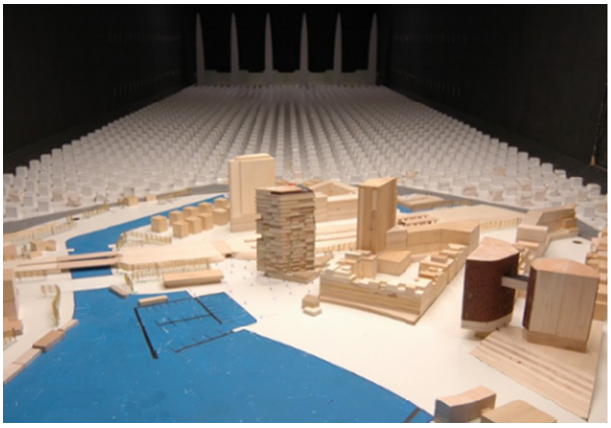


Figure 14. A wind tunnel test of a physical model of the building was carried out © Peutz.

8. Acoustic design

Laboratory and on-site testing was completed to ensure that the acoustic design limited any crossover of sound between the apartments. This is an elevated risk for this type of project because of the extensive exposed timber elements – particularly in the living spaces, where there are no ceilings. Arup went beyond the existing acoustic requirements for residential projects in the Netherlands, which are some of the most stringent in Europe. To determine acoustic performance in those high-risk areas, a section of the floor build-up was tested for both airborne and impact sound isolation. With the lower mass of the hybrid floor system, low frequency sound isolation was the determining factor in overall acoustic performance. During construction, further tests were carried out on site to provide additional reassurance on the acoustic performance of the system (Fig. 15).

9. Fire safety

HAUT pushes the boundaries of what is possible with high-rise timber design. Local building codes do not

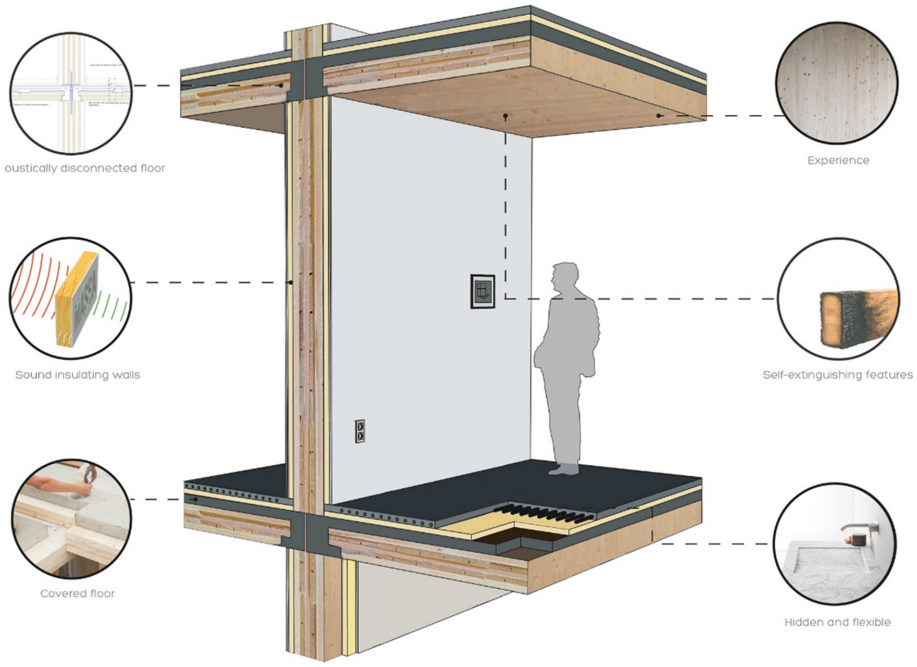


Figure 15. To determine acoustic performance, a section of the floor build-up was tested for both airborne and impact sound isolation © Team V.

address the additional fire risks inherent in tall timber buildings. The bespoke fire engineering design needed to address those fire risks, ensuring adequate means of escape and structural stability in fire situations, and mitigating the risk of fire spread. Arup called on its global expertise to carry out a rigorous review of the project, developing solutions that brought the design in line with international best practice. This led to additional fire safety measures being implemented in the building.

The fire risks that needed to be addressed in the bespoke fire safety design revolved around the height of the building, and the use of load-bearing CLT walls and exposed timber ceilings in the apartments. As timber is a combustible material and the architectural intent was to expose the timber at the ceiling, this fire hazard had to be addressed. The fire safety engineering assessed the likelihood and consequences of an extended fire duration and fire spreading beyond the compartment of origin. The performance-based fire strategy identified and managed those risks.

The Dutch building code does not require sprinkler protection in residential buildings of this height, but to contribute to a robust design, sprinklers were included. Also, to reduce the volume of exposed timber, a double layer of fire-resistant panels were installed to protect the CLT walls. The panels also improved the acoustic performances and are an example of an integrated design approach which enhanced the building redundancy and its quality. Laboratory fire testing was carried out in Belgium on the fire-resistant wall panels, with furnace tests providing both data and giving a practical demonstration of the compliance. Additional fire tests were carried out in Vienna to demonstrate the charring rate of the exposed CLT floor system. The tests determined the extent to which CLT panels burn over time, and helped determine the type of adhesive used. The choice of adhesive was critical to reduce the risk of CLT adhesive bond line failure in fire (so called char delamination) and to control the charring rate of the timber. Excessive charring could result in an unpredictable fire outcome and additional fire load.

By engaging Arup's international global fire safety engineering network and its extensive global research, the firm used the project to develop and formulate design solutions that can now also be used to enable the sustainable design of other mass timber high-rise projects. As a result of this global knowledge sharing, Arup has now been



Figure 16. Arup's fire team is supporting the development of additional guidelines to aid with amendments to local building codes © Jannes Linders.

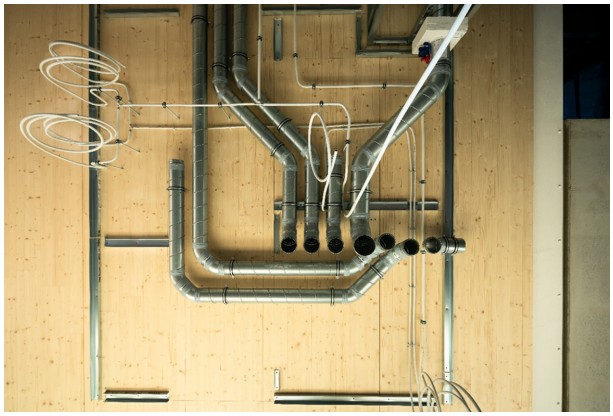


Figure 17. Distribution of the building's services required careful coordination to meet the structural, acoustic and fire safety requirements © Jannes Linders.



Figure 18. A performance-based fire engineering approach was adopted to manage the fire risk of the exposed timber ceilings © Jannes Linders.



Figure 19. HAUT is the tallest timber-hybrid residential building in the Netherlands © Jannes Linders.

asked to support the development of additional guidelines to aid with amendments to local building codes. The firm is also influencing changes to regulations around the use of timber in construction in the Netherlands, particularly for large scale and mid-rise to tall timber buildings (Fig. 16-19).

10. Groundbreaking

With its focus on reducing carbon footprint even before it was built, HAUT won the International BREEAM Award 2018, and following its opening, it won the Het Houtblad Timber Building of the Year 2022 award, which recognises the best timber building in the Netherlands. In addition, it was certified BREEAM Outstanding – an acknowledgement awarded to only a handful of high-rise residential buildings globally, and the first residential project in the Netherlands to achieve this sustainability certification.

Appendix

Project credits Developer Lingotto Architect Team V Architecture, Do Janne Vermeulen, Thomas Harms, Job Stuijt, Bart-Jan Hopman, Onno van Ark Timber engineering Assmann beraten + planen and RWT Plus Contractor J.P. van Eesteren Timber sub-contractor Brüninghoff Acoustic consulting, building physics, building services, fire safety,

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