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Haut – A 21-storey Tall Timber Residential Building

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Abstract

This paper reflects on the structural design of Haut; a 21-storey high-end residential development in Amsterdam, the Netherlands. Construction started in 2019 and is in progress at the time of writing. Upon completion in 2021, Haut will be the first residential building in the Netherlands to achieve a 'BREEAM-outstanding' classification. The building will reach a height of 73 m, making it the highest timber structure in the Netherlands. It contains some 14.500 m^2 of predominantly residential functions. It features a hybrid concrete-timber stability system and concrete-timber floor panels. This paper describes the concepts behind the structural design for Haut and will touch upon the main challenges that have arisen from the specific combination of characteristics of the project. The paper describes the design of the stability system and -floor system, the analysis of differential movements between concrete and timber structures and wind vibrations. The paper aims to show how the design team has met these specific challenges by implementing a holistic design approach and integrating market knowledge at an early stage of the design.

Keywords: Tall Timber Buildings, Mass Timber, TCC Floors, Holistic design

1. Introduction

Haut is a 21-storey residence, located in Amsterdam, the Netherlands. It will reach a height of 73 m, making it the tallest timber building in the country, and incidentally one of the tallest in the world upon completion. In addition, it will be the first residential high-rise project to achieve a BREEAM outstanding classification in the Netherlands. The project is the result of a design competition initiated by the municipality of Amsterdam, in which sustainability aspects were highly appreciated in the scoring. This challenge was met by proposing a design that prioritizes the use of (mass) timber structural elements over other structural materials, thus minimising the structures embodied carbon.

The competition was organised in January 2016, and the start of construction was in 2019. At the time of writing, construction of the structure has progressed to the second floor, which is also the first hybrid timber floor. The building features a public plinth, which timber structure has already been completed. The remainder of the structure is to be completed in 2020, completion of the building is scheduled for 2021. The project was commissioned by the Amsterdam based developer Lingotto. The main contractor is JP van Eesteren, working with Brüninghoff for the assembly of all timber structures. Arup provided all technical design services for the project, including structural engineering, building physics, fire safety, sustainability and building services. Team V is the architect for the project.

This paper provides a high-level description of the choices that were made during the design, the design challenges and the structural solutions. In this process, it has become evident that each of these choices were influenced by three central characteristics of the project: the height of the building, its residential function and the conscious decision to use mass timber as much as possible. The goal of this paper is to explain the answers that have been formulated to these technical challenges for Haut, in order to further develop existing knowledge on timber high-rise projects. In this way, the authors hope to contribute to further development and innovation in the use of mass timber in large scale and tall building projects.

Figure 1. Construction site in June 2020.

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Figure 2. Artist impressions. (source: Team V / Zwartlicht)

2. Design Concepts

2.1. General Concepts

The plot for Haut is located alongside the Amstel river at the edge of Amsterdam's city centre. The beautiful views that a high-rise project at this site can provide for its residents have been considered a prime quality from the very start of the design process. The architectural concept of Haut therefore relies on façade transparency, providing residents with lots of daylight, and unobstructed views of the city and countryside. Due to the project's high sustainability- and quality ambitions, mass timber was considered the most suitable option for this development. The choice for timber as a structural material leads to a significant reduction of the buildings embodied CO_2-footprint, compared to a similar development in any other structural material. By exposing the structural timber in the buildings ceilings, the aesthetic qualities of the structure are incorporated into the architecture.

2.2. Structural Concepts

In order to accommodate the desired unobstructed views, a load-bearing façade structure was ruled out at an early stage. Timber high-rise typologies relying on braced frames or CLT-panels in the façade were therefore not an option. The structural design relies on internal load bearing walls, which may function as separation-walls between residences as well. Floors consist of prefabricated timber-concrete composite (TCC) panels, which are supported on top of the CLT load bearing walls. Wherever the floor edges are not supported by a load bearing wall, glulam downstand beams are introduced. These beams are designed to transfer façade- and balcony loads and provide additional stiffness to the floor. They double as a tension ring around the perimeter of the floor, transferring diaphragm forces and acting as a structural tie. All residences have balconies extending beyond the façade, which are designed to be attached to the floor edges using steel brackets, with thermal breaks. This allows the contractor to first apply the façade, minimizing the time the timber structure is exposed to weather influences. The apartments in the 'wedge-shaped' north part of the building feature can-tilevering floors. These floors are realised with steel- and concrete edge beams, supported by two concrete columns. An alternative in timber would require large members, compromising the unobstructed views from these corner apartments.

The substructure consists of a two layer basement, the ground floor and first floor, which have been constructed in concrete. This provides a robust 'plinth' supporting the timber tower. From the first floor upwards, the gravity system consists of load bearing timber walls supporting the TCC floors, spanning in one direction. The lateral stability is provided by a concrete core and two CLT walls, which help to resist torsional effects resulting from wind loads.

Figure 3. Artist impressions. (source: Team V / Zwartlicht)

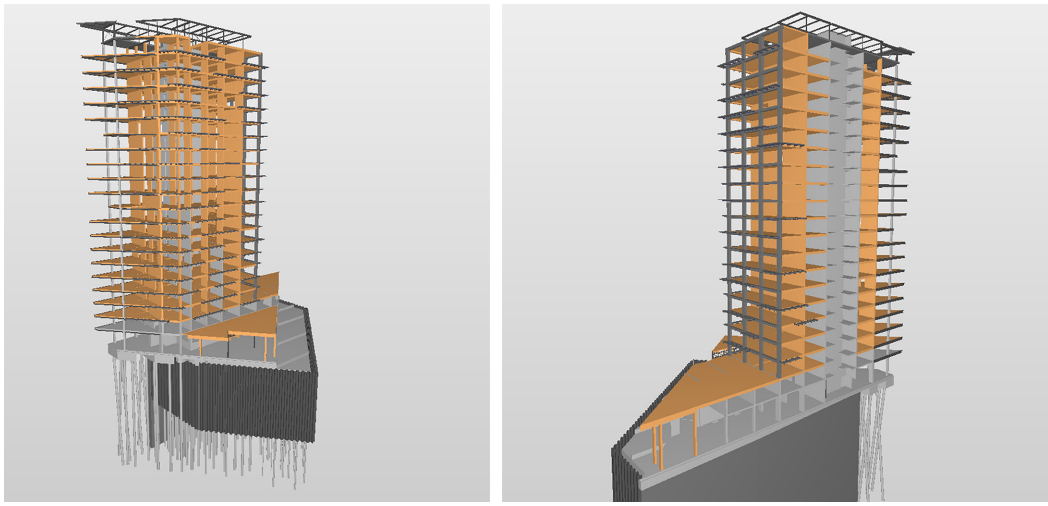

Figure 4. Building Structure.

The foundation design consists of ground displacing steel screw grout injection ('Tubex') piles. In addition, a load bearing diaphragm wall was required along the edge of the building plot. The foundation design was mainly governed by stiffness demands, and heavily influenced by the local soft soils, the presence of a pre-existing embankment and data cables which could not be moved.

3. Design Challenges

3.1. Stability System

3.1.1. Design

Keeping the projects ambitions in mind, the stability system was designed to leave the facades unobstructed. Initial studies showed that this ruled out the possibility of a full timber stability-structure, as the internal wall dimensions were insufficient to provide sufficient lateral stiffness. Two hybrid options were explored in parallel during the early stages of the design: a steel-timber hybrid and concrete-timber hybrid lateral stability system. The steel-timber hybrid system was based on CLT shear walls combined with a single steel braced frame, where the concrete-timber hybrid system relied on the same CLT walls, combined with a concrete core.

The main design challenges in the steel-timber scheme were twofold, and related to the lateral stiffness of the CLT shear walls. Although the stiffness of CLT itself is comparable to (cracked) concrete, the stiffness of a CLT wall consisting of multiple panels is highly influenced by its panel-to-panel connections. It was estimated that using typical connectors would reduce the global stiffness of the wall by some 70%. The proposed solution to this issue consisted of the implementation of a full height

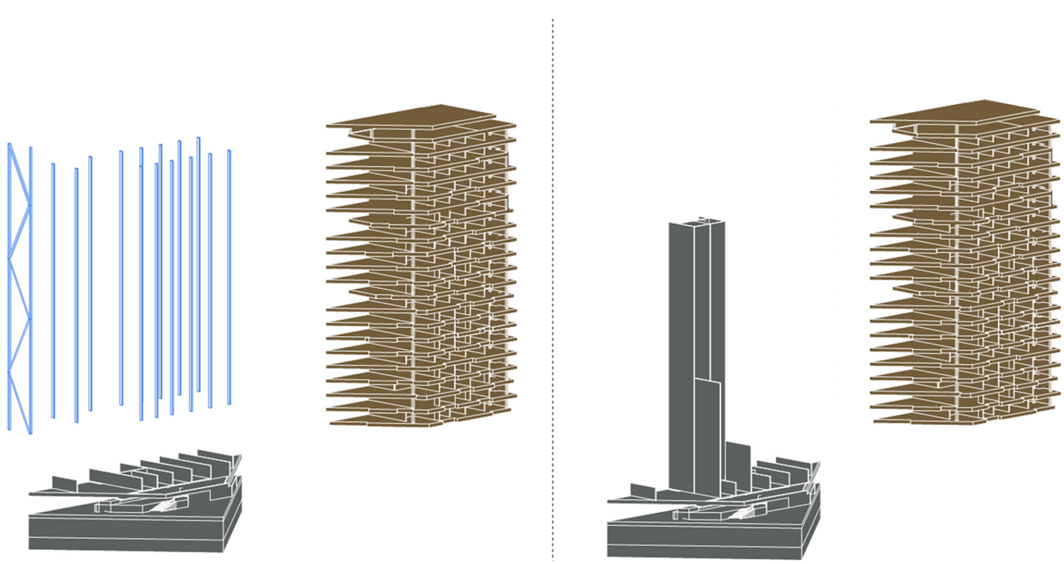

Figure 5. Stability system, steel-timber hybrid (left) and concrete-timber hybrid (right).

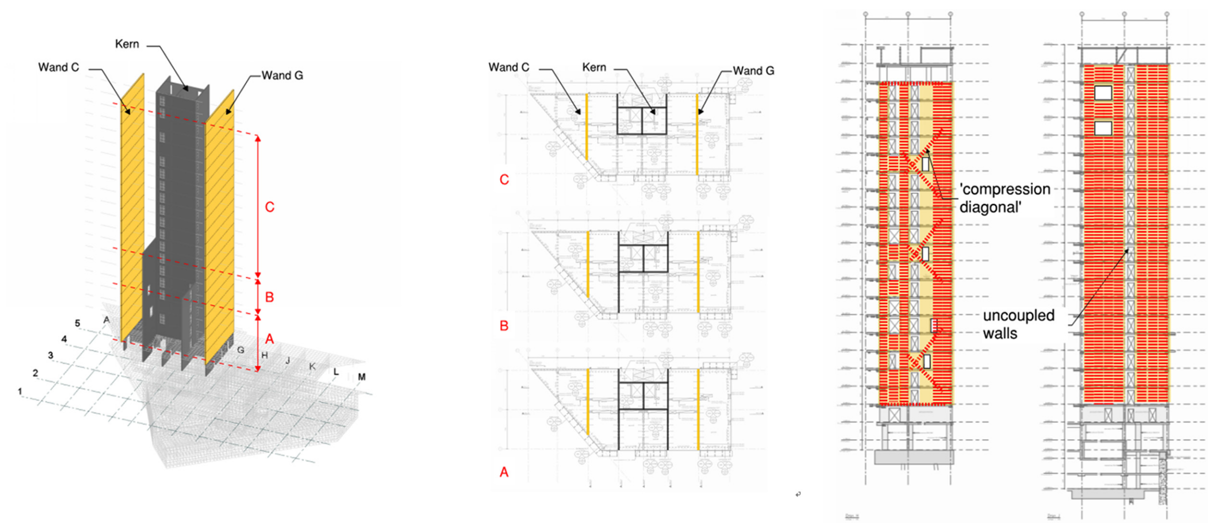

Figure 6. Lateral force resisting system (left) and elevation of CLT shear walls.

steel tie along the height of the wall. The second challenge resulted from functional demands of residential architecture; the architectural plans demanded a number of penetrations through the stability walls. Typically, no stiffness is attributed to lintels in CLT walls, as their moment capacity is insufficient for adequate coupling of walls. Therefore, a series of wall penetrations positioned directly above each other would have seriously compromised the global stiffness of the walls. This issue was resolved in close collaboration with the architect, placing wall penetrations in a 'staggered' pattern (see figure 6). This approach ensured the wall elements would function as a single -coupled- wall, rather than two separate -and therefore much weaker- individual walls.

The concrete-timber lateral stability system consists of a slender concrete core, and two CLT shear walls. A specific challenge in the design of this alternative was that for architectural reasons, the concrete core could only be placed eccentrically in the plan. This eccentricity introduces torsional effects under wind loads, increasing lateral deflections and wind induced vibrations. To reduce these effects, the load bearing CLT walls are designed to be part of the stability system. For the same reason, the concrete core is stiffened by extending its 'flanges' up to a particular height (see figure 6).

After the preliminary design phase, the steel timber-hybrid was compared to the concrete-timber system. Based on this comparison, the design team reached the conclusion that the concrete-timber hybrid would be the best fit for the project. The choice was driven by the following aspects:

- The concrete-timber alternative did not require a steel braced frame, providing flexibility in floor plans and reducing steel tonnage;
- The additional mass of the concrete core increased the performance of the structure with regards to wind induced vibrations and lateral deflections;
- The detailing of the steel strips in the steel-timber alternative was considered challenging and costly, as this would require a fully stiff tensile connection, while accommodating the shrinkage of the CLT walls;
- The embodies carbon of the concrete-timber alternative was considered lower, as the significant reduction in steel usage outweighed the adverse effects of the application of a larger volume of concrete.

Therefore, the concrete-steel hybrid system was not only perceived more feasible, but also more sustainable.

3.1.2. Analysis

The system is statically indeterminate, and lateral deflections are influenced by many factors. To determine expected maximum lateral deflections and perform sensitivity studies, two FEM-models were created.

The first model was a 3D-model of the entire lateral load-bearing system, including the concrete plinth, basement and foundations. The model was mainly used as a means of assessing total deflection and the sensitivity to stiffness of individual structural elements, including the foundations. In this model, the CLT shear wall is represented by a beam element with manually defined stiffness properties, allowing for an estimation of the influence of CLT material properties, connections and wall openings. To validate this estimated stiffness of the CLT wall, a second -more detailed- model was introduced.

The second model consists of a 2D-model of the CLT wall, including specific wall openings, orthotropic material behavior 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-model, allowing for a check of the initially assumed stiffness.

The stiffness of the CLT-walls depends on many factors, and although thoroughly analyzed, there will be a margin of error in any prediction of it. In addition, there was no prior experience with CLT stability walls on this scale. Therefore it was decided to only rely on the CLT walls in the serviceability limit states (SLS). The core has been designed to transfer full wind loads in the ultimate limit states (ULS).

3.2. Wind Induced Vibrations

If Haut were to have a full concrete structure of similar height, wind induced vibrations would probably not be considered in the design process. After all, there is plenty of experience which such buildings to conclude that demands will be met, even without analyzing these explicitly. Because Haut's hybrid structure is a lot lighter, wind induced vibrations were considered a risk and where investigated in detail.

With regards to wind-induced vibrations, the resulting accelerations at the top floor depend on stiffness, mass and damping of the structure. The first two aspects can be determined within a reasonable margin of error. The damping ratio is more difficult to predict. Due to the innovative character of high-rise structures in timber, and the large differences between structural system of the realised projects, the available data does not offer a definitive insight into appropriate damping values. For this project, a value of 1,5% structural damping was adapted for purposes of checking the wind-induced vibrations. The design team intends to measure accelerations after completion.

To calculate the expected maximum accelerations due to wind induced vibrations, a modal analysis was performed on the 3D-model of the structure described earlier. The dominant fundamental periods were determined, both represented orthogonal modes. It was of importance to prevent a dominant torsional mode, because this was believed to dramatically increase accelerations at the top floors. Based on a number of sensitivity studies, an upper bound for the governing acceleration was determined at 10 mg for a 1 year return period, using the method outlined in the NBCC [1]. This acceleration complies with the demands as stated in the Dutch national annex to Eurocode 1990 [2].

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.

3.3. Floor Build-up

The floors play a critical role in Haut's design, as they are key to the construction sequence, the stability system and many of the strict comfort criteria that were expected to be met for the residential units in Haut. In addition, the ambition was to leave the structural timber exposed where possible for architectural reasons. The floor system that was deemed to meet these requirements best, was a prefabricated timber-concrete composite (TCC) floor. This type of floor consists of a CLT plate (160 mm), with a concrete top layer (80 mm). In this build-up, the two layers collaborate as a hybrid system in which the CLT takes tension forces, and concrete takes the compression. Shear between the two layers is transferred by means of a series of notches, that are milled out of the CLT. The ratio between CLT and concrete is adjusted in some cases, to allow for thinner floors where these are required, for example to accommodate thermal insulation in loggia's. In this way, the floor system provides flexibility to allow for local deviations in the architectural design.

Another reason for choosing a TCC floor over a full CLT plate is its mass. This additional mass increases acoustical performance, has a beneficial influence on footfall induced vibrations, and helps to increase performance with regards to wind induced vibrations as well. Extending the concrete layer to the full height of the floor at both load-bearing ends of the plate, allowed for a 'platform' type wall-to-floor detail. This has significant benefits to the construction sequence. This would not have been possible using CLT plates, as it would introduce large cross-grain stresses in the timber.

The main challenge in the detailing of the floors was the integration of acoustical- and structural design aspects. To achieve proper diaphragm action in the floors, the individual plates are to be connected in-plane. Due to

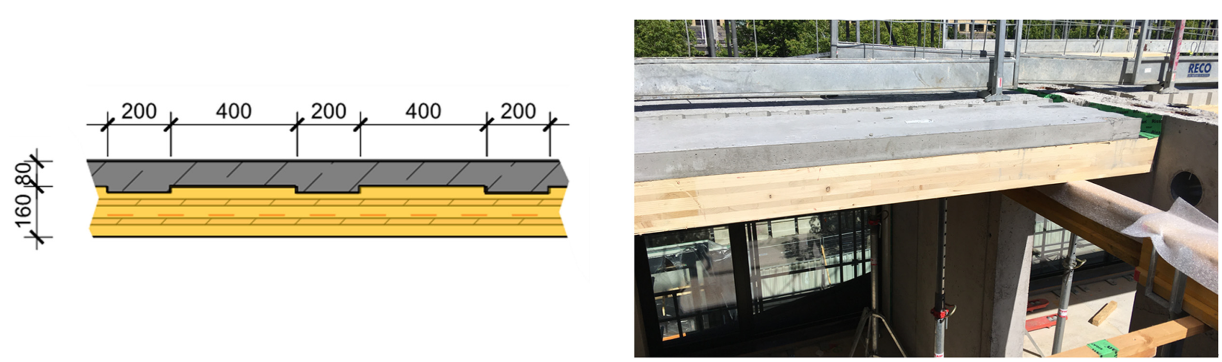

Figure 7. Floor build-up.

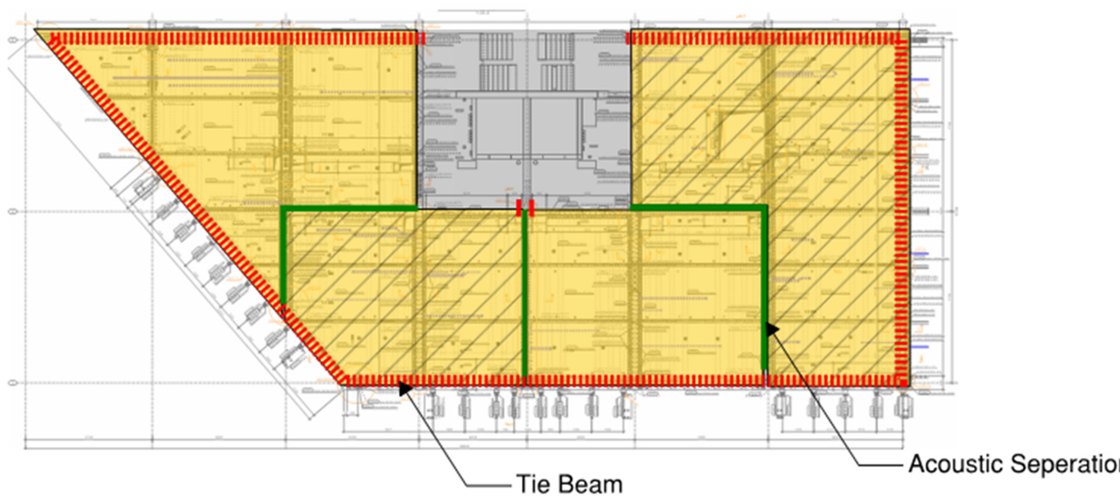

Figure 8. Diaphragm principle.

the low mass of the floors and walls, it is important to acoustically decouple floors wherever they cross separating walls between residences. Several solutions to resolve this problem where considered, before the final design was determined. Based on preferences related to constructability, the contractor came up with an optimisation of the initial detailing, in which the floor was essentially divided into multiple diaphragms, one for each residence on a floor. All of these sub-diaphragms are connected to the structural core and CLT stability walls, but remain largely decoupled from each other. Along the perimeter of the floor diaphragm, a ring beam ensures the separate diaphragms will act as one under wind loads. This ring beam doubles as a horizontal tie with regards to the robustness strategy.

3.4. Differential Movements

A number of floor fields are supported by a concrete 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. Although this issue is a common challenge in high-rise design, it would not be considered significant for a structure of this height, consisting of a single material. The combination of timber and concrete requires the issue to be studied in greater detail, despite the limited height of the tower.

This was also acknowledged in the design of Brock Commons [3], in which some projections were done with regards to the expected differential movements. Similar studies were performed for Haut. Based on these studies, the -unmitigated- final axial shortening on the top floor of the two projects was determined. Haut was expected to experience slightly higher movements which were mainly attributed to the greater height of Haut and the more conservative assumptions on the moisture content of the CLT. Contrary to Brock Commons, Haut features load bearing walls rather than columns, which complicates the mitigation of these movements.

If the walls in Haut were to actually undergo a *differential* movement of the predicted magnitude of 48 mm, it would lead to various architectural and functional issues. However, that number does not include the movement of the adjacent concrete structural elements. To determine the maximum differential movement, the shortening caused by elastic-, creep- and shrinkage-effects were calculated for the course of the construction and lifespan of the building, for three governing spans in the building.

The occurring differential movements depend on many factors, and are expected to be subject to change during construction and over the course of the building's design life. Therefore two scenarios were analysed, the first of which represents a best estimate for the various starting points, the latter representing a worst-case scenario. For a number of positions, the expected movements were calculated over time, yielding a maximum value for

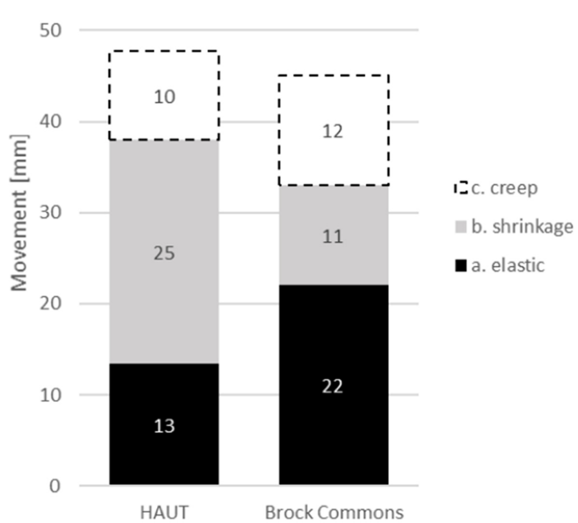

Figure 9. Expected Axial shortening of load bearing elements [3].

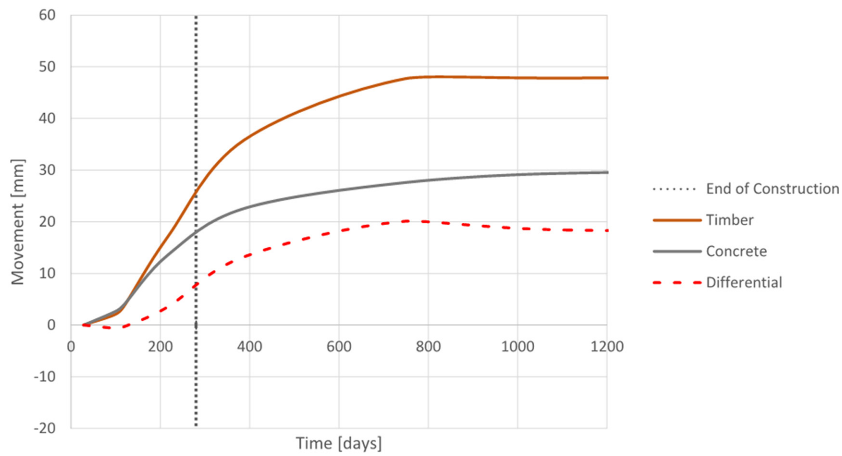

Figure 10. Differential movement over first 1200 days of design life.

differential movement at a certain point in time. From these analyses, a maximum differential movement of ca. 20 mm was determined between the core wall to the CLT wall, occurring at the 21st floor. This value is considered comparable to non-timber structures of similar height

No requirements were found in relevant design codes. The design team decided to adopt a requirement of span/500, which is equal to the demands that the Dutch National Annex to Eurcode 1994 [1] describes for structural elements that support 'partition walls prone to cracking'. Although no such walls are envisioned this demand seemed suitable due to the presence of brittle finishes (e.g. bathroom tiling).

In an unmitigated situation, the differential movements would not meet this criterion. Therefore, a number of changes were incorporated in the design with the sole purpose of limiting differential movements:

- To increase creep and shrinkage effect, the concrete core is constructed using in-situ concrete, rather than assembled from prefabricated concrete elements;
- Material of the columns at the cantilever in 'wedge' of the building were changed from steel to concrete, as the creep of concrete will partly offset the timber's shrinkage;
- Rotation is concentrated in lintel beam for load bearing walls adjacent to concrete core (see figure 11)

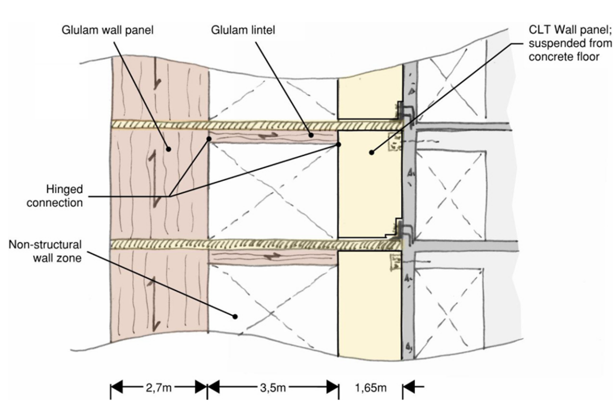

Figure 11. Expected Axial shortening of load bearing elements.

As a result of these changes to the design, the issue of differential movements is considered entirely manageable by implementing techniques commonly used in construction. The moisture content in the timber elements will be monitored during construction, along with the occurring movements in these elements and the concrete core. The contractor has developed a protocol to mitigate possible deviations from permissible values, by slightly adjusting heights at which the timber elements are mounted.

4. Conclusions

Haut is an ambitious project, aiming to provide high quality for its residents. In addition, Haut is innovative in its choice of structural materials. This paper has provided an overview of the design principles that were developed to meet the projects high demands, and it describes the specific challenges the project has posed to the design team. These challenges find their origin in the specific combination of characteristics of the project: the height of the building, its residential function with open facades and the conscious decision to use timber structures wherever possible. It is the combination of these factors that shaped Haut's design.

Only a handful of timber structures of similar size and height has been realised at this point. Therefore, many aspects of Haut are unique. This has required an explorative attitude from all parties involved, and a holistic approach to the design. In the structural design, this attitude manifested itself in a high number of studies into various aspects. These studies often required a return to first principles, or reliance on expert knowledge pre-existing in Arup or industry partners.

Due to the immense positive influence a timber structure can have on a projects embodied carbon footprint, it is believed that timber is an inevitable alternative and/or supplement to the use of steel and concrete in modern construction. The design of Haut shows that challenges associated with building in this material can be overcome. At completion, the goal of designing a sustainable yet high-quality residential building will have been achieved, marking a new milestone in the development of mass timber high-rise structures. The knowledge that has been acquired in the design process will aide designers to recognise relevant design challenges in the early stages of design for future projects.

5. Acknowledgements

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