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HYBRID STRUCTURES IN HIGH-RISE BUILDINGS: THE USE OF APPROPRIATE MATERIALS

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ABSTRACT: Architectural and engineering evolution has seldomly been characterised by a smooth transition, but rather by rapid changes. Currently, we are living in the time of a “sustainability revolution” and “timber renaissance”. Based on the recently emerging awareness for sustainability, a new architectural and construction language has developed. This requires a complete review of the old materials used in the last two centuries in favour of more “sustainable” and “natural” ones. This new approach has sparked a dynamic debate about construction materials. Since wood is the only regrowing building material, there is a natural inclination to believe that building with wood is good for the environment. But under which conditions is this really the case? What should we build with wood? What is the best way to achieve an optimal solution? This article examines the current state of the building industry with a holistic approach, exploring the use of structural timber and its combination with other materials for the design of medium and high-rise buildings.

KEYWORDS: Sustainability, embodied carbon, circularity, timber, hybrid structures, high-rise building.

1 INTRODUCTION

Timber is without a doubt the oldest building material ever used. However, following the advent of steel and reinforced concrete, the use of this material was almost exclusively limited to small constructions, such as family homes. The recently emerging awareness and profound interest in sustainable development, as well as the introduction of new engineered timber materials, such as Glulam or Cross Laminated Timber (CLT), have given this material a comeback, and as a result the construction of tall buildings made entirely or partly of timber is experiencing a boom on a scale never seen before.

Even though timber is the only renewable building material and there is a natural inclination to believe that building with timber is good for the environment, the environmental benefits of using it are not unequivocal. Critique has been expressed at the fact that only a portion of the harvested wood can be utilised as a building material. Additionally, the high energy demand required for the drying process of the wood as well as the problem of deforestation have sparked interest amongst critics.

Although this article does not aim to find answers to all these complex questions, we examine the benefits and drawbacks of using timber as a building material. This article does not claim to be exhaustive but is merely intended to give the audience an overview and some key points characterising design with timber and timber-hybrid constructions. With a holistic approach, we try to evaluate the feasibility of timber as a construction material in comparison to and in combination with other technical solutions and materials, also analysing environmental and financial aspects to achieve greater benefits for people and the planet.

2 THE CHALLENGE

Rising temperatures, melting glaciers, floods, desertification: All these well-known topics – summarised under the term “climate change” – are no longer just potential problems for the future, but already a reality. As we know, the above-mentioned aspects are closely related to us humans, to our activities and ultimately to the emissions we produce. Accounting for almost 38% of total global CO_2 emissions, the construction industry is one of the main contributors to climate change. From this, 28% is related to the operational energy, while the other 10% are attributed to so-called embodied carbon. This includes energy associated with the construction, demolition, and renovation of buildings as well as the extraction, production, transportation, and installation of all necessary elements [2]. Conventional building materials are responsible for around 2 billion tonnes of CO_2 emissions annually [5]. If we assume that on average, 50 trees would have to grow for one year to absorb 1 tonne of CO2, that would mean that we would require 100 billion trees to offset these emissions.

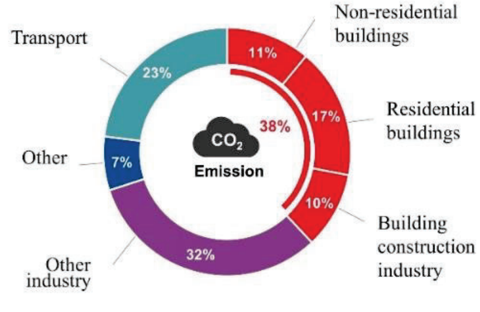

Figure 1: *Emissions in the Building Sector (© Arup)*

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These figures alone make it clear that reducing CO_2 emissions is a very ambitious goal. In addition, two other aspects must be considered: exponential growth of the world's population and the limitation of available non-renewable raw materials.

According to the United Nations: Today, the world's population is more than three times larger than it was in the mid-twentieth century. The global human population reached 8.0 billion in 2022 from an estimated 2.5 billion people in 1950. It is estimated to rise to over 10 billion by 2060 [8]. This means that the world's population will have quadrupled in almost 100 years and the demand for buildings and infrastructure – considering the rising standard of living – is going to increase exponentially.

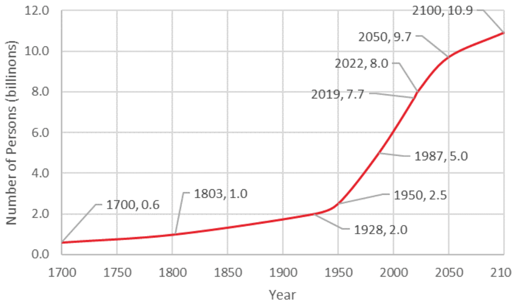

Figure 2: *World's population (©Arup, source: United Nations)*

Conventional building materials like reinforced concrete are composed of slow-renewable or completely non-renewable raw materials such as sand and aggregate. Concrete is one of most used substances in the world, second only to water, and it is the most used building material, twice as much as steel, wood, plastic and aluminium combined. According to the World Economic Forum, demand for sand mining has tripled in the past two decades, reaching 50 billion tonnes per annum in 2019 [7]. Sand mining or aggregate extraction – where sand and gravel are removed from riverbeds, lakes, oceans, and beaches for use in construction – is happening at a rate faster than the materials can be renewed, which is having a huge impact on the environment.

Figure 3: *Sand mining (© Dmitry Rukhlenko)*

For all these reasons, the most important matter of our time is a multiparametric challenge named sustainability: the necessity to build for an exponentially growing number of people using fewer non-renewable raw materials and producing lower emissions.

Dealing with this challenge requires a change in design and construction philosophy, not merely a change in materials. In other worlds, it requires the definition of a new architectural and structural language.

The first step of this revolution should be to consider limiting the construction of new buildings (aiming to the paradox build nothing) and instead transforming, reusing and retrofitting existing structures. In parallel, the focus should be on optimising the structure using materials wisely, using low-emission materials such as timber or recycled materials where appropriate, and conventional materials such as reinforced concrete where necessary.

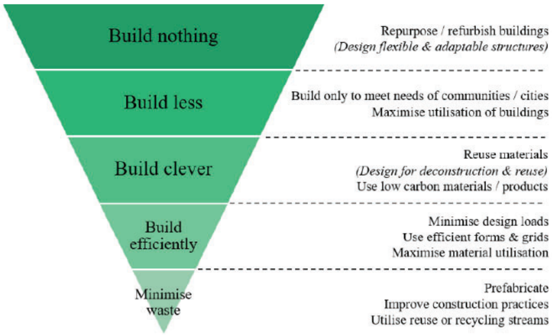

Figure 4: *Sustainable Design scheme (© Arup)*

3 SUSTAINIBILITY

3.1 What really is sustainability?

After decades in which the construction industry – except for few players – only aimed at minimising costs, a reorientation is taking place making sustainability one of the main targets. Defining the goal (e.g., designing a sustainable office building) is easier than defining the objectives or the way to get there. In fact, for each individual project there are a variety of approaches that can lead to a more sustainable outcome, and only the experience of the designers and the wisdom of the client can help to define the right solution for the specific project.

For example, in the project Coal Drops Yard in King's Cross, a derelict industrial site from the 19th century was transformed into a new shopping district for London. The design was refined and engineered to retain as much of the existing structure as possible, while upgrading building performance. In this project, it was possible to achieve an exceptionally sustainable result even with almost no use of timber.

***Figure 5:** Coal Drops Yard, London (© Hufton Crow)*

3.2 Industrial-based and / or bio-based material?

The transition between industrial-based materials like concrete or steel, to bio-based materials like timber is a turning point for the entire building industry, affecting investors, architects, and engineers. Engineered timber offers the possibility of creating a new visual language and at the same time poses new challenges in terms of structural design as well as building physics, acoustics, and fire protection. Exposed timber also modifies the internal climate of buildings and has a positive effect on the wellbeing of inhabitants and users (biophilia).

Mass timber has relatively decent strength, but it also has its own specific characteristics and limitations, which call for a change in the construction techniques and design concepts. Currently, we can see a general tendency to replace conventional materials with this "new one" by forcing the "new material" into traditional structural schemes. This leads to a tendency to use timber everywhere without considering whether other materials such as reinforced concrete or steel would be more suitable for a particular purpose, which in turn can lead to significantly higher material quantities, thus having an adverse effect on the costs associated with the construction of the building.

3.3 Materials follow purpose

To achieve a truly sustainable design on a large scale, ideally in every new project, we believe that a new "manifesto" for the use of materials must be established: materials follow purpose. Since the amount of building materials – and this also applies to timber – is limited, we must use them wisely and use timber, concrete, or steel to achieve an overall material reduction. With this principle in mind, we can experiment with new configurations and define a new architectural and structural language that reflects the demands of our time, such as sustainability, while considering the material properties.

3.4 Circularity, prefabrication, and modularity

The use of timber in hybrid structures opens new possibilities for the construction industry, namely prefabrication and modularity. Thanks to these two methodologies, construction time can be drastically reduced, construction costs optimised, and, above all, waste reduced to a minimum. The life-cycle of prefabricated systems can be extended beyond the once-off life of the building. The fact that the elements are not monolithically connected (as opposed to reinforced concrete structures), but can be assembled, dis-assembled, and re-assembled increases the possibility of using the individual components even after their first "life". This transforms the building industry from a linear process from construction to disposal to a circular process in which the individual components can be used multiple times and ideally never become waste. Circular economy principals are driving reuse and recycling of entire areas of the built environment. Refurbishment plays a vital part in this economy, and the whole industry needs to prepare for the future life of buildings. The principles of the circular economy enable far more than just decarbonisation. They help us to keep finite resources and healthy materials in endless loops. They help us to eliminate waste and to regenerate natural systems. Furthermore, they also help us to keep assets flexible and adaptable for any future use.

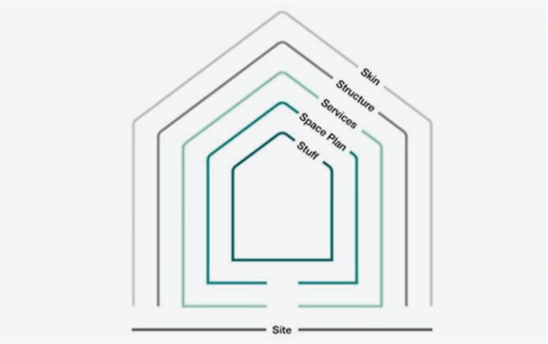

***Figure 6:** Circular principles (© Arup)*

Using circular principles, the various components are designed for assembly Design for manufacturing and assembly (DfMA), but also for disassembly (DfD). In addition, the construction-relevant information is retained throughout the life of a building, making its reinvention more likely and less complicated. Under these principles, the different components are designed considering a different lifespan based on the technical possibilities and not only on the first use of the building. In this process, some components such as the structure have a longer lifespan – a correctly designed and maintained structure can last much longer than the typical 50 years specified in the regulations – while others such as the façade or the building services tend to require replacement at shorter intervals (usually 20-25 years). Modular building systems can be added to, expanded, downsized and repurposed, as needed. The modules can even be easily relocated from one place to another as needed. This is, for example, the main concept of the project "Adaptive Buildings", developed by Arup in collaboration with Futur2K, using a modular timber structure as the main part of the project.

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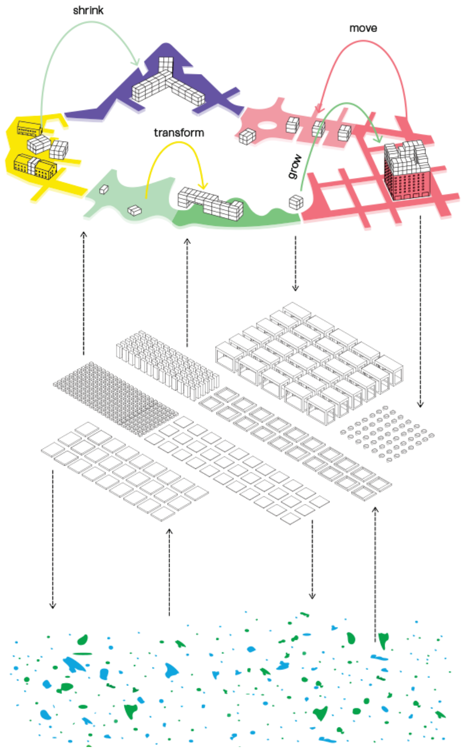

Figure 7: *Adaptive buildings (© Arup)*

3.5 Legislations, certifications, and financial aspects

Emerging sustainability regulations in individual countries are increasingly imposing mandatory sustainability requirements and financial incentives for sustainable design. It has also been proven that sustainable buildings are more attractive on the market and generate higher revenues. These facts have a direct impact on the use of timber, and from various experiences we have found that the additional costs associated with using this material are offset by the financial benefits and higher revenues.

Certifications (BREEAM, LEED, or DGNB) play an important role in defining the materials used. Timber structures can help projects acquire the desired sustainability rating score. For most clients, the direct higher revenues from a Gold or Platinum certified building or the reduction of risk in their investment strategy by decarbonising their portfolio is one of the main reasons for using timber. Other clients really embrace that as a framework for innovation and to unlock new growth opportunities for instance by rethinking their asset operation strategy or by applying new circular business models for the built environment.

Construction-grade timber and engineered forest products are some of the highest valued products from trees. This suggests that the structural use is important for economies that rely on forestry, and to further the development of the forest itself by planting new trees.[9]

4 PURE TIMBER STRUCTURES

4.1 Timber: a lightweight and strong material

Timber has a strength (parallel to grain) similar to reinforced concrete: hardwood is slightly stronger, and softwood slightly weaker, although timber cannot match modern high-strength concrete in compression. Timber is less stiff than concrete, and both materials are far less stiff and strong than steel. However, timber has a low density compared with these other conventional structural materials [9]. For this reason, considering strength-to-weight and modulus-to-weight ratios softwood performs similarly to steel by those measures.

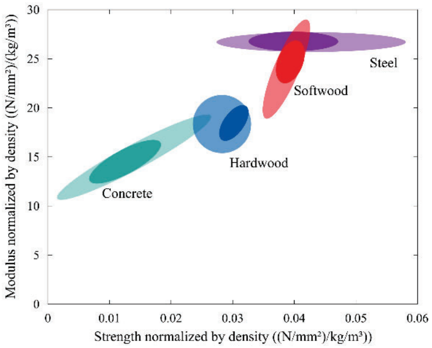

Figure 8: *Compression strength and modulus of elasticity materials normalised by density. (Source: [9])*

This suggests that timber is a particularly structurally efficient material in structures, or parts of structures, in which a high proportion of the load to be resisted is the self-weight of the structure. Examples are roofs, some bridges, and the gravity load resisting system of tall buildings [9]. However, in structures for which the load to be resisted is largely independent of the weight of the structure – such as the wind load on a tall building – the higher absolute strength of steel or reinforced concrete may make them more efficient, in terms of the amount of material required [9].

In an earthquake, the force imposed on the structure depends strongly on its mass, with heavier structures experiencing larger seismic forces. Light timber residential buildings have therefore been observed to perform well in seismic events [9]. The seismic behaviour of taller timber buildings is an active field of research. WG3 of COST Action CA20139 "Holistic design of taller timber buildings", of which one of the authors (Guido Nieri) is a member, is researching this topic (see [4]).

As wood is 6 times lighter than reinforced concrete and almost 20 times lighter than structural steel, the use of timber as a construction material has numerous advantages. The reduced weight (especially when compared to reinforced concrete) can lead to the reduction in foundation sizes or avoiding the necessity for deep foundations, thus resulting in a more economical design. Furthermore, it increases the possibility for vertical extensions of existing buildings. Indeed, by using a more lightweight material than concrete or steel, it allows for quicker construction and minimises strengthening of the existing structure. By doing so, structures that might have otherwise been demolished or lain empty can be modernised using eco-friendly building standards. They can retrofit existing structures and create additional income with new leasable area. For example, in the project 80M Located in Washington D.C. lightweight engineered timber was used as a carbon-friendly construction technique to retrofit the existing structure with three additional storeys.

Figure 9: *Project 80M, Washington D.C. (© Ron Blunt)*

Complex geometries can be produced economically and efficiently by utilising timber. This is perhaps wood's most important advantage. Being both lightweight and machined to high tolerances means that wooden buildings can be assembled rapidly when compared to concrete, which requires several activities to construct (falsework, formwork, reinforcement, pouring) and then curing time after construction before follow-on trades can gain access to the structure [1]. BIM to CNC fabrication allow designers and fabricators to create a smooth transition between design and production [1].

Figure 10: *Metropol Parasol, Seville, (© Hufton + Crow)*

4.2 Possibilities and limitations of pure timber structures in medium and high-rise buildings

The use of pure timber structures for medium and high-rise building is still a challenge today, but – up to a certain height – certainly feasible. Projects like the Mjøstårnet tower in Norway, with its 18 storeys, is the best example of today's possibilities but also of the critical aspects. In this case, for example, additional mass (screed/concrete slabs without composite action) have been added to control sway and vibration, and the diagonals of the stabilisation system are visible and sometimes limit functionality.

A structure's complexity increases with the overall height of the building. For low-rise buildings (3 to 5 storeys), where the forces to be resisted are relatively low, shear wall systems mainly made of CLT panels can be used.
The structural and mechanical behaviour of cross laminated timber and its use to support lateral loads has been extensively researched in recent years. Arup department of Specialist Technology & Research in London (Lawrence, Abeysekera, and Smith) has produced detailed research and design guidelines and have published their findings [12] on which this chapter, among others, is based.

To resist lateral loads, the individual walls act primarily as vertical cantilevers subjected to bending. The stiffness of the connections plays an important role in the stiffness of an individual wall and that of the entire system. The fact that each wall is divided into several interconnected panels and that different loads may act on the individual connections, which are characterised by different stiffnesses, leads to quite complex mechanical behaviour even when observing an individual wall. This can be theoretically described by the superposition of 4 different behaviours, which are shown in the following figure.

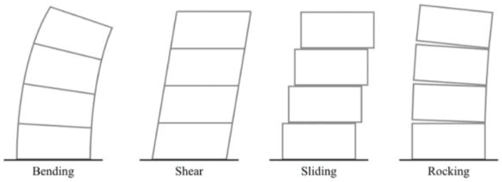

Figure 11: *Mechanical Behaviour CLT walls (© Arup, I. Abeysekera)*

Furthermore, stability systems generally consist of different walls connected to form a statically indeterminate system. However, since timber, like glass, is a brittle material, there is no redistribution of forces based on plasticity, therefore determining the actual load path is not straightforward. For these reasons, the correct dimensioning of the structural components and the connection is very demanding. In addition, questions about the robustness of the system, especially for use in seismic zones, have not yet been clarified and the guidance given in codes is very limited.

As timber structures increase in height, all-timber stability systems can become increasingly expensive (due to the cost of connections). In addition, due to fire safety requirements, CLT walls must usually be completely covered (typically with plasterboard), so that the wooden structure is completely invisible. For these reasons, CLT stability systems are not very common.

Alternatively, timber frame systems arranged around the perimeter can be provided by bracing. The bending moment (e.g., from wind loads) is converted into tension and compression forces in the bracing, but diagonals are required limiting functionality. Moment-bearing structures (rigid frames) rely on the interaction between beams and columns that transfer the moment caused by horizontal forces directly at the connection. The rotational stiffness of the connection influences the horizontal deflection of the building, and the strength of the connection determines the load-bearing capacity of the structure. Due to the typically low strength and stiffness of timber moment connections, this type of system is not very common.

4.3 Key design criteria: acoustics and vibration

Although being lightweight has certain advantages in terms of transportation and erection, it does inevitably make the building more susceptible to dynamic excitation issues and sound transmission. The required acoustics and vibration performance of timber structures can be achieved by careful layout and design and should be addressed at an early stage of the design process so that proper cost allowances can be made.

4.3.1 Vibration

Vibrations are usually the governing factor in the design of mass timber buildings. For slab design, the comfort criteria for human-induced vibrations is reached when the bending stresses in the elements are still far below their load-bearing capacity. Longer spanning floors especially, need careful attention to vibration from an early design stage. Simplified approaches like static deflection methods can, in some cases, lead to lively floors which attract adverse comment. For this reason, conducting a full dynamic computational analysis at an early stage is recommended [1]. Test results on real buildings also demonstrate that damping by structural and non-structural elements also play an integral role in defining the dynamic property of the system.

4.3.2 Acoustics

Best practice in acoustic design of building projects using standard reinforced concrete structures is well established and the regulations cover the typical configurations comprehensively. However, this is not the case when it comes to timber. Due to the low mass, to meet acoustic requirements additional mass may need to be added to the floor build-up. This can be in the form of an additional layer of either concrete, or a similar rigidly bonded mass layer (e.g., bound gravel). A wet screed on sound insulation or a raised floor system with acoustic absorbers are needed to create a mass-spring-mass system which takes away some of the benefit of the low-mass timber slab. Decoupling of floor panels or screed from the CLT slab by using an acoustic batten build up or acoustic insulation on top of the CLT helps to improve acoustic insulation and is an important part of maximising impact sound insulation. Furthermore, it is also important to consider sound flanking transmission.

4.4 Fire protection

In addition to the structural, acoustic and vibration requirements, the building must have sufficient fire safety and fire protection systems for occupant life safety, prevention of fire spread and protection of fire fighters. Considering the brevity of this article and the complexity of the topic fire design in timber construction, only a few comments are addressed here. A detailed analysis of this topic is demanded in separate articles (e.g., Barber et al. [13],[14]). There are a range of fire safety systems that can be implemented to achieve safety goals, such as sprinkler protection, or reducing the area of exposed timber through the installation of non-combustible panels (e.g., gypsum boards). Different local regulations, approaches, and interpretations of some critical aspects of timber design lead to project-specific challenges that affect the design process and the building itself. The requirements for structural fire resistance rating increase with the height of the building and can sometimes even be met without additional protective layers, but only by considering sacrificial depths in the design of the elements.

4.5 Costs

As cost is the driving parameter in the industry, these aspects cannot be neglected. Although for a long time the difference between timber structures and standard structures was relevant, currently it looks like carefully designed timber systems (using timber only where it is possible and really the best choice) can economically challenge traditional concrete structures.

4.6 Holistic approach

As is evident from the topics presented in this chapter, the complexity of timber high-rise buildings is neither linked to individual subjects nor limited to individual disciplines. In each project it is necessary to find bespoke solutions that represents the best compromise between different requirements. Unlike other construction materials, where a single aspect can govern the design, in the case of timber, it is a combination of requirements which drive the design, which in turn is what makes timber unique. As shown by the experience in daily practice at Arup, but also shown by different institutions and research (e.g., COST Action CA20139), a holistic approach is required to improve the performance of taller timber buildings and increase their competitiveness when compared with other materials. For this reason, only with a multidisciplinary design strategy is it possible to maximise the real advantages of timber.

5 HYBRID STRUCTURES

The term “hybrid structures” describes systems that consist of two or more structural materials, in this case: timber and reinforced concrete or steel. The combination of materials can be limited to a single structural component, such as timber-concrete composite panels, or to the entire building, such as the use of reinforced concrete cores as a stability system for horizontal forces. In both cases, the term “hybrid” is used as an antithesis to the purist approach described in the previous chapter. The reason for combining the two materials is the need to improve the properties of timber related to such aspects as acoustics, vibrations or fire performance.

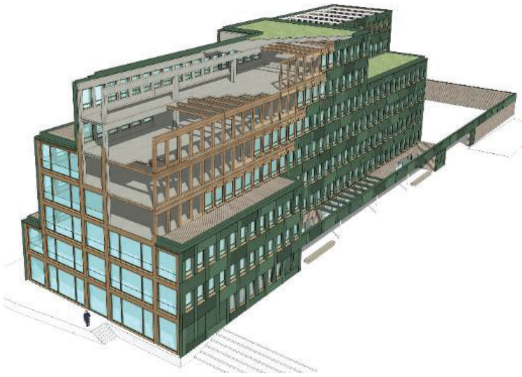

Figure 12: *Projekt H7 in Münster, Germany. (© Andreas Heupel Architekten BDA)*

In projects like H7 in Münster (Germany) or the project HAUT in Amsterdam the design was driven exactly by this priniple: timber where possible, concrete and steel when necessary. As a result, the foundations, basements, and cores were built using concrete. The concrete cores provide stability to the structure and contribute to the fire safety of the building. Based on this it was possible to achieve a highly optimised design with a total embodied carbon reduction of 50% when compared to a conventional building. Furthermore, looking for ways to use as much timber as technically possible, Arup embarked on a quest for an innovative and affordable technical solution comprising almost entirely of precast timber-concrete composite floor systems.

Figure 13: *Project HAUT, Amsterdam (© Jannes Linder)*

5.1 Stability Systems

As introduced in the previous chapter, lateral support for seismic and wind loads is one of the major challenges associated with the design of high-rise buildings in general and for timber buildings in particular. Wood-based lateral timber-bearing systems, such as CLT walls/cores, braced wood frames (but also more advanced post-tensioned/self-centring systems), are feasible design options today. However, the fire safety requirements, the uncertainty about the stiffness of the elements and the connections and thus about the load path, the required tests, and the time and costs involved in obtaining official approvals would have had an adverse impact on the cost and complexity of the building. For this reason, in daily practice for medium and tall timber buildings, the primary lateral support for earthquake and wind forces is usually provided by concrete cores.

As discussed in [11], a typical 50-60 m tall timber high-rise building usually consists of a concrete core (to meet fire protection, acoustic and structural requirements) in combination with timber or timber-concrete composite floors and possibly timber columns along the façade (at relatively short intervals). For taller buildings, additional bracing for sway vibration and comfort requirements or additional stability systems are usually also required.

5.2 Slabs: Timber Concrete Composite (TCC)

Timber Concrete Composite (TCC) consists of a timber beam or panel (glulam or CLT) and a concrete slab mechanically connected by a fastener, e.g., with self-tapping screws and/or notches in the timber beam/panel. From a structural point of view TCC can double the imposed load carrying capacity and have up to three times the flexural rigidity of traditional timber floor systems, when compared to the same depth system acting non-compositely, leading to reduced deflections and decreased susceptibility to vibrations. The combination of timber and concrete is not only an efficient mechanical use of materials, but also offers better fire performance and acoustic properties compared to pure timber systems.

Even though the system itself could be more expensive than a standard slab system, the overall cost of TCC floors can compete with other floor systems when cost savings such as fast construction and reduced foundation costs are considered. There are many variations on the construction market at present, and there are projects where a timber or hybrid floor system are very competitive with conventional reinforced concrete. In addition, the savings in embodied carbon make TCC an attractive construction method compared to concrete/steel counterparts. The concrete topping also provides a good level of thermal mass that can help reduce building operating costs and energy consumption when combined with an effective ventilation system.

Recent research suggests that an optimal slab build-up could consist of two layers: a structural layer of reinforced

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concrete, reduced to a minimum to achieve structural performance, and a top layer of wet screed to improve acoustics. The validity of this solution has been corroborated in various projects such as the recently completed 21-storey HAUT in Amsterdam [1]. The deployment of this new technology comes with its own challenges, as these new systems are not fully regulated and different systems with different short- and long-term structural behaviours and costs are available on the market. In addition, as is common with composite structures, the possible future separation of the two materials and their reuse has not yet been fully explored.

Currently, Arup is conducting internal research to incorporate latest design codes and optimise the TCC systems to provide best performance for structures, dynamics, acoustics, and fire.

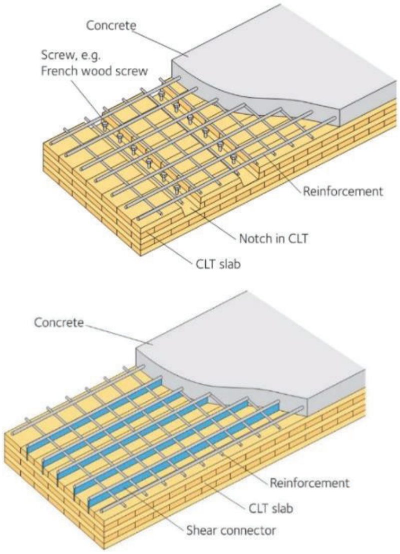

Figure 14: *Timber Concrete Composite Floor System (© Arup, S. Tang)*

5.2.1 The mechanics of the system

The typical shear connections used for TCC are not infinitely stiff. Due to the sliding and creep of the connection, there is only partial composite action. This must be considered when determining the proportion of bending and axial stresses in each element and in the design. Due to the partial shear interaction, the assumption that plane sections remain plane is invalid for the whole composite section. The analysis must check the overall stresses resulting from the bending moments in both the concrete and timber in combination with the axial compression and tension forces respectively owing to the shear transferred across the connection.

The section of the Timber Eurocode (EC5) covering TCCs has been revised and published as a Pre-Standard (CEN/TS 19103:2022-02). This standard has been updated and includes new design methods. This underlines the importance of TCC and will promote its wider application in practice.

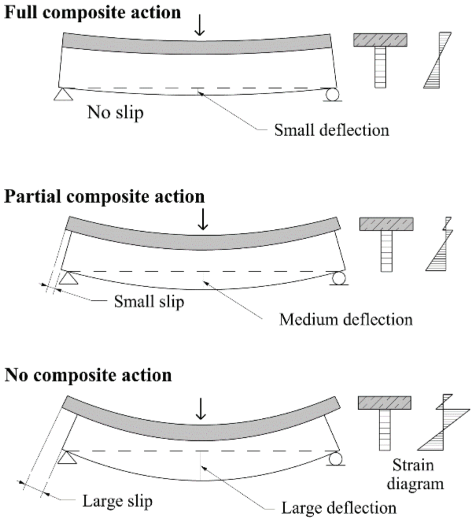

Figure 15: *Mechanical behaviour of TCC (© Arup)*

5.2.2 Possible shear connections

The most important aspects of the Timber Concrete Composites are, of course, the shear connections. These are the elements that connect the timber and concrete layers and allows the materials to act together as one structural material. A stiff connection between the two materials enables a slimmer design of the slab system, whereas a softer connection results in larger cross-sections. Shear connections are not only relevant from a mechanical point of view, but also play a key role for the cost and constructability of the system. The most common shear connectors in TCC are:

- Screws with partial embedment into the timber and partial embedment into the concrete,
- Perforated plates (HBV mesh) glued into the timber and protruding upwards into the concrete,
- Notches (indentations) in the timber beam or panels into which the concrete is poured.

In addition, many combinations of dowels, epoxied bars, nail plates, etc. have been explored in the past. Unique and new types of connections are usually more complex and expensive or lack data from tests. They are also usually not very stiff and sometimes do not have sufficient ductility, which limits the performance of the composite. Two promising new types of connections still being researched are:

- Glued connections: these have almost not slip.
- Micro-notches defined and tested by Prof. Frangi et. Al from ETH Zurich.

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5.2.3 Multi-span continuous timber–concrete composite floors

TCC floors which have been researched and built are almost exclusively simply supported single spans. Multi-span continuity can be used to enhance the stiffness, strength, robustness, and ductility of TCC floors [10]. These configurations are currently only being investigated in research or test laboratories, with very few innovative projects exploring their possible applications in practice.

5.3 Vertical structural systems

The vertical system of a building is composed of walls and columns. While the walls can also serve as a stability system (as described in the previous chapter), the columns are usually only loaded in compression. In the case of columns, the material is used as it is in a living tree. Up to 10-15 storeys (30-60 m), the use of timber columns is practically state of the art, although not without challenges. The requirements for fire protection increase with the height of the building and can usually be met without additional protective layers, but only by considering sacrificial depths in the design of the elements. In Germany, for example, the required fire resistance time is 90 minutes up to a height of 60 m, and 120 minutes above 60 m.

The load-bearing capacity of the vertical structural systems is usually not the main challenge. Taller buildings simply require larger cross-sections. The only limits here are the architectural requirements and the costs. Major challenges are the shortening of the timber columns and the definition of an adequate robustness concept that prevents e.g., progressive failure in case of column loss.

5.4 Timber skyscraper

In terms of vertical load capacity, it would be possible to build a skyscraper several hundred metres high entirely with timber columns. However, there are strong reasons associated with fire performance, resistance to disproportionate collapse and carbon impact resulting from inefficient use of the wood for not doing so.
For these reasons it seems much more appropriate to think about hybrid solutions aimed at limiting (but not avoid completely) the use of reinforced concrete on a large scale and defining a smooth transition to the new era. With this vision in mind, it would also be possible to consider implementing the construction principle of medieval towers, with stronger materials (such as reinforced concrete) in the lower part and lighter materials (timber) in the upper parts of the structure. Alternatively, a combination of reinforced concrete superstructure with a modular timber system could also be a viable alternative.

Figure 16: *Case study on combination of reinforced concrete superstructure with modular timber system (© Arup)*

6 Conclusion

Sustainability is no longer a choice, but an obligation for each of us towards future generations. Sustainability cannot be reduced to the simple approach of using a sustainable material but rather is a multi-parametric challenge. Sustainability is a necessity to enable us to build for an exponentially growing number of people using fewer non-renewable raw materials and producing lower emissions. To properly address this challenge, we need to go beyond considering a single aspect such as energy efficiency or embodied carbon and instead approach the multiple faceted issue in a holistic manner to avoid an over-simplistic approach that can only lead to greenwashing.

As with other technical breakthroughs, architects, designers, engineers, and all consultants should explore the limits of technical feasibility for new applications in a safe and responsible manner. This requires a good understanding of the materials and the behaviour of the components, backed up by rigorous analysis and extensive testing. Timber should be used where it adds value to the project, considering all technical, economic and environmental parameters along with the properties and limitations of the material.

Hybrid constructions are one of the best choices for medium and tall buildings, as they use the best properties of timber, concrete, and steel without the need to oversize some components to compensate for the limitations of pure timber (e.g., acoustics, vibrations) or have the high embodied carbon and material consumption characteristic of reinforced concrete construction.

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