Tall Timber Buildings: Application of Solid Timber Constructions in Multi-Storey Buildings

Andrew Waugh\textsuperscript{1}, Matthew Wells\textsuperscript{2} and Mathew Lindegar\textsuperscript{3}

\textsuperscript{1}Waugh Thistleton Architects, London, UK
\textsuperscript{2}Techniker Consulting Engineers, London, UK
\textsuperscript{3}Techniker Consulting Engineers, London, UK

Abstract
In our paper, we will use our Stadthaus scheme to demonstrate that solid timber construction is a financially viable, environmentally sustainable and beautiful replacement for concrete and steel in high-density housing.

Constructed entirely from cross-laminated timber from the first floor upwards, Stadthaus is the tallest timber residential structure in the world. The nine-storey building is the first of this height to construct load bearing walls, floors and cores entirely from timber. The tower houses twenty-nine apartments with a neighbourhood office on the ground floor. Stadthaus was assembled using a structural cross-laminated timber panel system produced in Austria by KLH. Each panel is produced from Spruce planks glued together with a non-toxic adhesive. The waste timber is converted to fuel, which powers both the factory and local village. As the prefabricated panels arrived on site they were immediately craned into position and fixed in place. Four carpenters assembled the eight-storey structure in twenty-seven days. The speed of the construction was especially relevant in the densely populated environment, as was the lack of noise and waste, creating far less intrusion on the local community than a traditional concrete frame construction. The entire building was completed within forty-nine weeks of starting on site, estimated to be a saving of five months over a notional concrete frame building. This method of construction is also incredibly accurate, and a healthy environment to both work on and live in. Upon its completion the building had zero defects and 100\% tenants approval. The unique structure of the building is a result of the practice’s research in reducing the carbon emissions not only of the finished building but of the whole build process. The production of concrete and steel are very energy intensive, pumping tons of carbon dioxide into the atmosphere. In complete contrast timber stores carbon as it grows; our research shows that Stadthaus stores 186 tons of carbon within its structure for its lifetime.
Introduction

Timber construction offers the possibility of minimal cost and no carbon footprint combined. Cross-wall high-rise structures, particularly residential buildings, have low stresses in their structural components. Walls and floors that are dimensioned to provide adequate acoustic separation and thermal performance have plenty of substance to resist the levels of applied loading encountered. This paper describes the design and construction of a nine storey cross-laminated timber apartment building in east central London and explores the factors limiting the height of future projects in solid timber construction. A preliminary design for a 25 storey tower is presented.

Cross-laminated Solid Timber

The Stadthaus apartment building in Murray Grove was made with solid timber walls and floors using the proprietary system of KLH UK Ltd [1]. The architects are Waugh Thistleton and the engineers are Techniker Ltd. The typical product is a panel of solid spruce formed of strips stacked in perpendicular layers and then glued under a pressure of 60 tonnes/m². As building components these units have reduced moisture movement and increased strength compared to unmodified timbers. Manufacturing plant is arranged to provide the maximum size of panel that can be readily transported, 2.95 metres x 16.5 metres in thicknesses of up to 32 centimetres. The biggest panels therefore weigh 15 tonnes, well within the range of standard mobile craneage. The panels are usually arranged to be mutually supporting (like a card house) or in folded plate assemblies. The joints are made as simple as possible using light metal fixings to disperse forces.

Description of Stadthaus

This apartment building provides one, two and three bedroom living accommodation on nine floors. All vertical load-bearing and lateral resistance is provided by wooden walls and cores making this building the tallest of its kind. (Figures 1-2). Foundations are bored cast in-situ reinforced concrete piles sized to accept the weight of a concrete framed building of similar size in order to safeguard procurement alternatives. The ground storey is also cast in-situ reinforced concrete framing providing more open
accommodation at ground level. The cellular spaces above are all cross-laminated timber cells. The lift-core and stairwells are independent structures within the building and are isolated from surrounding core walls and perimeter which provide the overall lateral stability of the structure.

![Fig. 1: External photograph of Stadthaus](image1.jpg)

![Fig. 2: Computer image of structure](image2.jpg)

The site was confined but accessible from local streets on two sides. No permanent craneage was required during the works. Once the foundations and ground storey had been placed the site was cleared and panels began arriving by lorry from the factory in Austria. Units were placed directly upon arrival and work proceeded at the rate of one storey completed every three days. The erection team comprised 4 carpenters. The site remained safe and clear of waste throughout the process. Rain-screen and windows were added from an external scaffold. The exposed timber walls and soffits proved very easy to fix to and finishing proceeded without incident.

**General Design Considerations**
Many types of building have now been constructed in massive timber; housing, schools, sports centres and hotels and a preferred approach to the material’s use has been developed by Techniker and Waugh Thistleton from this experience. Low-rise construction, up to five or six storeys, generally comprises platform construction with cross walls set perpendicular to one another with floors laid on top. Upper storeys bear on the side grain of the horizontal panels below. Fixings using long screws or screws in combination with angle brackets or plates have been developed for most conditions. Five key design issues have been resolved and tested at full-size.

**Fire** In buildings of solid timber charring is relied on for structural fire resistance. The cross-section is considered to progressively reduce during an incident and sufficient surplus material is provided to give adequate time for a fire to be controlled. Standard charring rates are set and tests have established the specific behaviour of timber from various sources. Close grain timber specified on the faces of panels significantly improves their fire resistance. For residential units the separations within apartments should have half-an-hour’s integrity, between apartments one hour integrity and between apartments and principle vertical circulation two hours integrity.

**Robustness** Panelised buildings are susceptible to progressive collapse; the loss of one component redistributes load or adds debris loading and leads to the sequential failure of other elements. A considerable part of the design work undertaken on Stadthaus was in the assessment of options to ensure the robustness of tall timber structures. Design research continues into the movement characteristics of these forms.

In the United Kingdom there is design guidance developed by the BRE to prevent catastrophic failure in timber frame construction of up to 6 storeys. This is directly applicable to massive timber construction. There is no EU guidance at the time of writing. Discussions with TRADA and the TFA have brought forth as realistic limit state criteria a notional shock load of 7.5kN/m² and the removal of a single wall length or floor panel.

These requirements lead to alternative design approaches. Ties between units can be strengthened to a sufficient level to resist anticipated accidents, blast loads or unexpected impacts. Our preferred route has been to exploit the over-structuring typical in residential layouts by conjecturing alternative load-paths
should any component be compromised.

We have therefore pursued a policy of ‘efficient redundancy’. Wherever possible floor panels are designed to span in two directions or to cantilever if a support is removed. Effective ties are provided between floors and walls using simple ‘off-the-shelf’ brackets and screws. The inherently high in-plane stiffness of the cross-laminating process provides ‘built-in’ redundancy in the form of wall elements which can span laterally if support beneath is removed.

**Fig. 3: Strategy to resist accidental damage**

**Fig. 4: Nail reinforcement at a bearing point**
**Movement** The control of movement is the key to the development of large timber structures. Engineered timber produces a material comparable in its dimensional stability to concrete and steel. The long-term creep movement of cross-laminated timber is negligible across the face of the panel and less than 1% across the grain. Similarly moisture movement is too small to measure over the panel surface and less than 2% cross-grain.

**Acoustics** The overall build-up of a cross laminated structure cannot be considered lightweight but some extra separations are generally required to achieve an adequate performance. Across party walls 2 layers of 9 millimetre thick plasterboard each side will achieve Building Regulations Part E requirements; externally a 1 centimetre air gap is needed. Between floors an acoustic ceiling should be adequate. For stairs and lift cores double wall construction is desirable with a 4 centimetre air gap.

The base cost of timber construction is currently about 10-20% more than that of a comparable reinforced concrete frame. There are several compensations at construction stage offsetting this cost disparity. Cross laminated panels arrive by lorry in erection sequence. They are lifted into place immediately with no storage, no waste and no wet trades. The site remains completely tidy at all times. The operations are repetitive and safe. Erection times are typically reduced by 30% with attendant savings in preliminaries. Secondary considerations include the simplicity and familiarity of surface fixing to timber. Errors can be relatively easily corrected on site with a skill-saw and holes added. The thermal emissivity of an exposed wooden surface is excellent at a value of 0.87.

**Very Tall Buildings High-Rise Design Considerations**

What are the theoretical and current practical limits on this form of construction? Where is further research needed? There is more strength capacity to be exploited. Economic viability hinges on both quantity of material and simplicity of detailing in more or less equal measure. The elasticity of timber and its relative softness are key to its future use in high rise buildings. If the simple platform construction currently being used is unmodified then a straightforward point block reaches 15 storeys with economic wall thicknesses. If bearing points are strengthened locally then two or three extra storeys might be added. The ratio of structural weight to floor area provided increases linearly with overall height. (Figure 5).
Techniker Ltd. have proposed a jointing method, taken from packaging design, to interleave wall and floor elements to form continuous vertical load paths down through the building. (Figure 6).

![Graph: Structural weight/floor area](image1)

**Fig. 5: Structural weight/floor area**

![Diagram: Improved joints](image2)

**Fig. 6: Improved joints**

Tie and bearing details can be improved in several ways. Hardwood margins could be added. Increase in tower height would then be possible to the point where the p/delta effect begins to govern wall thicknesses and hence costs. Nail plates at bearings could further improve capacities. Side plates can be
placed to act as ties to improve robustness and to transfer some additional loads. These are expensive.

With the materials now in use, heights then reach 25 storeys retaining economic wall thickness. The p/\(\delta\) effect becomes important. The tendency of a tall structure pushed off axis to pull itself over must be resisted by additional stiffness. (Figure 7).

![Figure 7: P/\(\delta\) effects on tall buildings](image)

Above 25 storeys a reinforced concrete core offers a conventional bracing provision without enlarging the poché of the plan. The outer edge of the building can then be opened out with simple vertical load bearing components. (Figure 9). Detailing can circumvent the problem of cross grain shrinkage at each floor level. (Figure 10). The differential movement of hull and core can be modeled as a time history and the load transfers assessed and allowed for. The elevation can be modeled to reflect the load conditions at each floor level. (Figure 11).

**Conclusion**

In summary the ethos of the material is to use it directly with the plainest details and construction methods possible. The underlying attitude has building as a populist, simple, noble activity. Very tall buildings could be constructed of timber throughout. A range of building scale suited to solid laminated timber will in due course present itself. There is still much development potential in this approach.
Acknowledgements

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Reference

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