Design of an 8 storey Residential Tower from KLH
Cross Laminated Solid Timber Panels

Megan Yates, FIStructE
Non-Executive Director
Techniker Ltd
London, UK

Matt Linegar, MIstructE
Associate Structural Engineer
Techniker Ltd
London, UK

Bruno Dujic, PhD
Civ. Eng., teaching assistant
University of Ljubljana, Faculty of Civil and Geodetic Engineering
Ljubljana, Slovenia

Summary

There are many prejudices against the use of timber for multi-storey buildings, primarily fire, movement characteristics and durability. The cross lamination process addresses all of these and provides an appropriate material for the construction of domestic medium rise buildings.

This paper examines the design decisions made to procure an 8 storey residential building in Hackney, London constructed from KLH cross laminated solid timber panels. It argues the case why this is an appropriate form of construction for buildings of 6-10 storeys and the design principles of working with the material in this way.

As a precedent this building should help strengthen and improve the design of multi-storey timber buildings not only in the UK but across Europe. To successfully achieve this, designers must respect the simplicity of design and detailing that leads to efficient timber structures. The boundaries of what has been achieved thus far can then undoubtedly be pushed further.

1. Introduction

We were approached by London architects Waugh Thistleton [1] to carry out a feasibility study on the viability of procuring the 8 storeys of residential accommodation in cross laminated solid timber panels built off a concrete podium transfer structure. This came from an environmental position and a drive to get timber more readily accepted in the UK construction industry.

The concept design had been developed with this in mind, with the flats generated in a (rectilinear) honeycomb pattern around a central core. This idea was conceived as a means to rotate the prescribed flat layouts on plan thereby allowing the Architect to get away from the repetitive facades that are so often generated by the stacked layouts of housing schemes; whilst mitigating the need for transfer structures. The client, property developer Telford Homes, supported the proposal, but naturally needed to be convinced of its viability at all levels having never procured a building in this way before.

There is a very clear logic behind the structural design of this building and a level of rigour required beyond what is normally expected by a design team to buy into the structural concept and respect the principles behind the design. The cross laminated solid timber panels form a cellular structure of timber load bearing walls, including all stair and lift cores, with timber floor slabs, and as such will be the tallest pure timber building in the world (Fig.1).
2. Cross Laminated Solid Timber Panels

Cross laminated solid timber panels by KLH are manufactured from timber strips glued in perpendicular layers (Fig.2) under pressure to create a product that has high in plane stiffness and can span horizontally in 2 directions [2].

The manufacturing process combined with the effects of cross lamination minimises swelling and shrinkage resulting in particularly stable timber elements. To form building structures the panels are generally joined with mechanical fixings at regular intervals to avoid concentrated loads and distribute the connection stresses to avoid the risk of overloading any one connection resulting in unzipping failures. Connection detailing is the art of good timber engineering and each project must consider this.

3. Structural Solutions Considered

In the current construction market in the UK a building of this form would normally be procured as an insitu reinforced concrete frame, set out on a domestic grid with flat slab floors which are suited to the spans that this generates, minimises depth of construction and gives good acoustic and fire separation. The project was originally conceived as a reinforced concrete frame and was programmed at 66 weeks.
This type of construction is generally combined with blockwork infill walls and where possible the columns are detailed to fit within the thickness of a 215mm wall. Floor depths are of the order of 250mm.

Alternatives that might be considered are mobilising the walls as load bearing elements – either in masonry, which would need to have vertical ties for disproportionate collapse, or reinforced concrete walls. Mobilising the walls as part of the structure is inherently efficient and providing there are adequate ties provides a robust structure with sufficient redundancy. Tunnel form construction is an economic way of achieving this, but relies on repetition along a linear grid.

Cross laminated solid timber was proposed as an economically viable alternative to a reinforced concrete frame. The economy is primarily achieved through programme gains that can be won as a result of the speed of erection and the fact that structure is architecture and follow on trades are greatly reduced. Fabricated in factory conditions in Austria (the transport miles of which were included in the carbon offset argument), the panels are manufactured to ±3mm tolerance. Time is required in the design phase to ensure a fully coordinated design to take advantage of the factory production line such that all openings and service penetrations are formed during the cutting process.

Although on paper the cross laminated solid timber scheme cost 30% more than a comparable reinforced concrete frame, the programme has been reduced to 49 weeks, giving a 17 week saving. In addition to this the construction plant requirements on site are reduced, which is significant given the constraints of the tight site.

UK planning currently requires between 10 and 20% of the energy of the building in use to be from renewable resources. This not only adds direct cost to projects but also often results in additional space requirements to accommodate the plant. In terms of the carbon footprint of the project, substituting timber for reinforced concrete results in significant reductions. A comparative estimate of the total carbon (including transport) of the two schemes was presented as part of the planning application. The carbon load of the building is effectively reduced by 300,000 kgs. This is offset against the estimated carbon (in the form of CO₂) produced in the generation of the energy requirement of the building in use of approximately 15,000 kg/year, equating to 20 years of the building in use (or 200 years at the current requirement of 10% renewables). This resulted in the renewables requirement being wavered. This not only resulted in the direct savings of the cost of the renewables, but also eliminated the need for a basement to accommodate the additional plant.

In global terms the two options studied came out cost neutral.

4. **Structural Form**

The external walls span between the floors to transfer wind loads into the floor plates; which in turn distribute the horizontal loads into the perpendicular internal and external walls. The walls are anchored to the concrete podium which transfers the stability loads into the foundations.

In accordance with EC5 the stability path needs to be verified for joint slippage due to racking loads. The number and arrangement of the internal and external walls means that this is negligible.

In the UK the height of the building at 9 storeys means that it is categorised as Class 2B under Building Regulations Part A3 [3]. In addition to designing the building to support loads from normal use there should be a reasonable probability that it will not collapse catastrophically because of misuse or accident.

There are three main approaches to avoiding disproportionate collapse of structures which in the UK at present only relate to reinforced concrete, steel and masonry structures. The approaches are to ensure that the building is adequately tied together, a check on notional removal of load bearing walls and finally where either of these two approaches cannot be justified then elements should be designed as ‘key elements’. These elements are then subject to an accidental loading of 34kN/m² which has arisen from loads generated during a gas explosion within a confined space.

At present in the UK there is no official guidance for the design of timber buildings to prevent disproportionate collapse and clearly to design any timber element and its associated fixings for 34kN/m² is extremely onerous. Advice from the Timber Research and Development Association
(TRADA) and the UK Timber Frame Association (TFA) suggests that multi-storey timber framed buildings should be designed to avoid disproportionate collapse thorough the application of adequate ties to resist a notional horizontal force of 7.5kN/m of wall and the notional removal of these walls [4].

We have therefore adopted this approach for the design of this building and we have provided sufficient redundancy such that any individual wall can be removed and the floor and wall above will not collapse. This has been achieved by ensuring primary floor panels are continuous over a minimum of two supporting walls and adjacent panels are staggered, see Fig.3. These floor panels have then been designed to either ‘double span’ or cantilever under accidental loads. Where the internal organization of the space does not make this possible an alternative secondary load path has been found. While the primary load path is generally direct floor to wall, the accidental load paths also mobilise the external walls as deep beams and the secondary span direction of the floor panels.

Fig.3: Typical structural floor panel layout

To achieve the required tie forces two approaches were considered. Firstly we looked at developing bespoke details that literally tied wall panels between stories clamping the floor panels in between. Although very robust this approach was too onerous in both terms of cost and constructability on site. Our second approach was to use standard ‘off the shelf’ brackets and plates at regular centers. Floor panels are also screwed directly through to wall panels below. This approach resulted in only two bracket/plate details and two types of screw throughout the building except at the junction with the concrete. Here a bespoke detail has been proposed which is designed only to resist the horizontal shear forces with the brackets designed for the tensile forces only, see Fig.4. This simple approach to the connections minimises the level of supervision and the risk of mistakes on site. Where horizontal forces due to wind loads etc. are particularly high the brackets are simply doubled
The high in-plane stiffness of cross laminated solid timber panels and its ability to span in more than one direction is critical to the robustness of the structure and minimises the risk of disproportionate collapse when compared with traditional timber framed buildings. If this were a dormitory block with total repetition throughout its height we could simply design all of the floor plates to double span but this would have very limited applications for the future of cross laminated solid timber design. As the design of the flats developed to suit the needs to the various user groups, inevitably some of the alignment and purity of the original ‘honeycomb’ diagram was lost. In addition to this the requirements of modern living for large open plan living spaces added to the complexity.

![Diagram of cross laminated solid timber wall panels](image)

**Fig.4: Typical connection details**

Although the building has generally been designed to minimise the compressive stresses in the wall panels, due to the nature of the construction i.e. wall panels sitting on floor panels sitting on wall panels and because of the change in floor layout half way up the building; the design strength in some floor panels is close to capacity because of the reduced compressive strength of timber perpendicular to the grain. To increase the capacity locally the cross laminated solid timber panels are reinforced using screws as shown in Fig.5.

![Diagram of load distribution and screw reinforcement](image)

**Fig.5: Timber reinforcing detail using screws**
5. Movement

For tall timber buildings it is important to control movement due to (load) creep (2) and moisture (3). The design mobilises all the internal cross walls as load bearing walls to keep the load distribution even and avoid concentrated loads. The compressive stresses in the walls are kept well within the permissible stresses such that movement due to creep will be negligible. Generally the building has been designed to ensure that compressive stresses within the wall panels are less than 50% of the maximum permissible compressive stress.

The cladding, finishes and vertical circulation are to be detailed to allow for the maximum expected movement between floors due to changes in moisture content and due to loading i.e. creep. To control and minimise moisture movement the panels will be protected on the journey to and storage on site. The end grain is the most susceptible to absorption of moisture and will be protected. Standing water on floors can track under the wall-floor junction and this is to be taped throughout construction.

5.1 Movement due to load (creep)

Long term Young’s Modulus of cross laminated solid timber, \( E = 300 \text{N/mm}^2 \) and permissible design stress perpendicular to the grain, \( f_{c,90} = 2.5 \text{ N/mm}^2 \) [2]. Therefore for a single KLH 146 TL cross laminated solid timber panel loaded perpendicular to the grain the creep total movement due to load is as follows:

\[
\delta = \frac{E \cdot \delta L}{L} = \frac{2.5 \cdot 146}{300} = 1.2 \text{mm}
\]

This figure is conservative as it not only assumes that the floor panels are operating at permissible design stress, but also that this condition exists under long term loading.

The cross lamination and manufacturing process of the KLH panels means that there is negligible creep in the plane of the panels.

5.2 Movement due to moisture

The cross lamination means that in plane shrinkage of the walls is resisted by stress building up in the glue line – the actual shrinkage is therefore negligible. However it is worth noting that for this reason fluctuation in moisture content must be avoided as in extreme cases of external use this will eventually result in splitting of the timber. Therefore for internal use we only need to take into account shrinkage across the floor panels:

Maximum moisture content at erection: 14 to16%

Minimum moisture content in use: 8 to 10%

Coefficient of moisture movement = 0.24% per % change in moisture content [5]. Therefore for a single KLH 146 TL cross laminated solid timber panel and 6% differential the total movement due to moisture is as follows:

\[
\delta = 0.24% \cdot 6% \cdot 146 = 2.1 \text{mm}
\]

5.3 Thermal movement

The regular jointing of the panels introduces adequate slack into the system to accommodate expansion and contraction of the timber due to changes in temperature.

6. Fire

Continental European regulations specify that the cores of buildings need to be built from non-combustible materials as a fait-accompli without any consideration of the actual performance.
Therefore, all of the examples of tall timber buildings that we have found have been built around reinforced concrete cores. While at one level this gives the designer an added sense of security, it actually goes against the grain of the design principles of cross laminated solid timber. The relative stiffness of the core is such that the majority of the stability loads will be transferred to the core – not only does this not mobilise the inherent in plane stiffness of the timber walls but it concentrates the loads adding complexity to connection detailing. In addition to this the two materials have different movement characteristics and therefore the connections and finishes must be detailed to accommodate this movement.

A fire resistance period of 90 minutes was specified to all structural elements. This is to be provided by 2 layers of plasterboard (60 minutes) and the charring rate of the cross laminated solid timber (30 minutes). However, the timber will generally be designed to achieve 60 minute fire resistance period to provide adequate redundancy calculated in accordance with EC5. However, this in itself is conservative as the timber starts to ‘self-protect’ once charring occurs and the rate of loss of section decreases accordingly.

7. Acoustic performance

Timber buildings have always been classified as poor in terms of their acoustic performance. This experience is mainly based on traditional timber framed buildings. Whether traditional or modern, timber buildings are super light structures compared with other traditional forms of construction such as reinforced concrete and masonry. Cross laminated solid timber panels have a significantly higher density than timber frame buildings, 500kg/m$^3$ or 50kg/m$^2$ for a 100mm thick wall panel. Cross laminated solid timber panels provide a solid structural core on which different, independent and separating layers can be added. The layer principal is the key method to overcome any acoustic or sound transfer issues. Together with University of Graz Building Physics Department, KLH have developed and tested a large variety of wall and floor build ups to match the varied requirements of each country throughout Europe. In countries such as Austria, Switzerland, Germany and Scandinavia the performance requirements are particularly high compared to other European Countries and in particular the UK. The requirements in the UK for residential developments are as follows:

- Party walls between apartments (horizontal) airborne: $D_{nt,w} + Ctr$ 45dB
- Party floor between apartments (vertical) impact: $L_{nTw}$ 62dB

With a consistent and economic layering strategy such as stud walls with 10mm air gaps in front of the party walls, floating floor build ups and suspended ceilings, the following values have been achieved with KLH cross laminated solid timber:

- Party walls between apartments (horizontal): $D_{nt,w} (C,Ctr)$ 63(-2,-8)dB
- Party floor between apartments (vertical): $L_{nTw}$ 46dB

It can be seen that the performance of cross laminated solid timber panels exceeds the UK requirements. However, there is room for improvement. In Austria residential buildings (mainly 4 stories high) are achieving even the highest requirements in Europe with cross laminated solid timber panels forming the primary structure.

8. Quality control

A key advantage for the use of cross laminated solid timber panels instead of traditional timber frame buildings is that the panels are produced and cut to the required shape and size at the factory. Routing and holes for services and connections can easily be incorporated within the panels and should be considered from the very beginning of the design to achieve the rewards of this manufacturing process. This increase tolerance in the material bring obviously benefits on site i.e. windows and door apertures etc.

For this project standardisation of panel sizes, one size for internal and external walls and one size for all floor and roof panels, has also been key to improve quality of the final building.
9. Conclusion

There are many prejudices against the use of timber for multi-storey buildings, primarily fire, movement characteristics and durability. The cross lamination process addresses all of these and provides an appropriate material for the construction of domestic medium rise buildings. Mortgageability is key to any developer and the biggest hurdle in the procurement of this project has been convincing the inherently conservative mortgage lenders to underwrite the material, due to the bureaucratic nature of the process.

Considering this we have in general adopted a practical and conservative approach to the design and detailing of this structure. This response has also been due to the lack of guidance and regulation towards the design of multi-storey timber buildings in UK. However, this has not been to the detriment of the architecture or the costs. This combined with standardisation and simplification of the connection details has resulted in a building structure that feels suited to construction in cross laminated solid timber.

As a precedent this building should help strengthen and improve the design of multi-storey timber buildings not only in the UK but across Europe. To successfully achieve this, designers must respect the simplicity of design and detailing that leads to efficient timber structures. The boundaries of what has been achieved thus far can then undoubtedly be pushed further.

10. Acknowledgements

Megan Yates is a Structural Engineer at Kalin Cuerel in Lausanne. Formerly a Director of Techniker Ltd. where she, together with Matt Linegar an Associate at Techniker Ltd. have developed the use of KLH cross laminated solid timber panels for the UK market, working in close collaboration with Karl Heinz Weiss of KLH UK. They are responsible for the structural design of this building.

Additional advice on the properties of KLH cross laminated solid timber panels and their application in construction was provided by Bruno Dujic of the University of Ljubljana, Faculty of Civil and Geodetic Engineering, Slovenia and Johann Riebenbauer of JR-Consult ŽT GmbH, Graz, Austria.

11. References


