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Author:	Matthew Wells, Creative Director, Techniker Ltd
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Tall Timber Buildings: Applications of Solid Timber Construction in Multistory Buildings

Matthew Wells

Author

Matthew Wells, Creative Director

Techniker Ltd
Consulting Structural Engineers
13-19 Vine Hill
London EC1R 5DW
United Kingdom

t: + 44 20 7360 4300
f: + 44 20 7360 4301
e: marketing@techniker.co.uk

Matthew Wells
Matthew Wells has over 30 years experience in the design of building structures and bridges. His particular area of interest is in developing the interface between structural design and architecture. In his role as creative director Matthew maintains an overview of the conceptual content of all the projects in the company. He has delivered a wide range of both new build and refurbishment structures including arts centers, housing, schools and offices as well as a number of public realm and infrastructure projects. He has taught at various schools of architecture and engineering including the Bartlett and Architectural Association and three years as external examiner at Liverpool University. He has served on the Architectural Association Council, the CABE Olympic review panel and is currently visiting professor of architectural engineering at the University of Leeds.

...2,000 feet

"Any structure over 2,000 feet tall is automatically considered a danger to aircraft."

Joann Sloane, US Federal Aviation Administration's spokesperson, on the possibility of supertall buildings. From "Supertall Buildings: The Dreams and the Realities," The New York Times, September 30, 1984.

"In buildings of solid timber, charring is relied on for structural fire resistance. There is no chemical fire resistance treatment as such. 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."

By far the "shortest" building submitted for the 2010 CTBUH Awards was the Stadthaus in London (see Figure 1). Standing nine floors and 29 meters (95 feet) tall, the multifamily building is indeed not very tall when regarded by height, but it does stand out as one of the tallest timber framed buildings in the world. Uniquely, not only the load-bearing walls and floor slabs are constructed out of timber, but also the stair and lift cores, making typical cross-bracing elements redundant.

Timber construction offers the possibility of minimal cost and no carbon footprint combined. Cross-wall high-rise structures – residential buildings in particular – have relatively 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 story 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 30-story tower is presented.

Cross-Laminated Solid Timber (CLT)

The Stadthaus apartment building in Hoxton, London was designed with solid timber walls and floors using the proprietary system of KLH UK Ltd. KLH is an acronym for KreutzLagen-Holz (Cross-Laminated Timber). The architect is Waugh Thistleton and the engineers are Techniker Ltd. The typical engineered panel is made of solid spruce, formed of strips stacked in perpendicular layers and then glued under a pressure of 60 t/m^2. As building components, these units have reduced moisture movement and increased strength compared to unmodified timbers. The manufacturing plant is arranged to provide the maximum size of panel that can be readily transported, 2.95 x 16.5 meter (9.68 x 15.13 feet), with thicknesses of up to 320 millimeters (12.6 inches). Therefore, the maximum size of panel weighs 15 tons, well within the range for use of a standard mobile crane. The panels are usually arranged to be either mutually supporting (like a card house) or as folded plate assemblies. The joints are made as simple as possible using light metal fixings to disperse forces.

Project Description

The Stadthaus 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 in the world. 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 story is also cast in-situ reinforced concrete framing providing more open accommodation at ground level. The cellular spaces above are all CLT cells.

Figure 1. The Stadthaus, Hoxton, London

The lift-core and stairwells are independent structures within the building and are isolated from the surrounding core walls and perimeter, which provide the overall lateral stability of the structure. The site was confined, but accessible from local streets on two sides. No permanent cranes were required during the construction. Once the foundation and ground story was placed, the site was cleared and panels began arriving by truck from the factory in Austria. Units were placed directly upon arrival and work proceeded at the rate of one story completed every three days, with an erection team comprised of four 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 tie into, and finishing proceeded without incident.

General Design Considerations

Many building types have now been constructed in massive timber (i.e., housing, schools, sports centers and hotels), and a preferred approach to the materials use has been developed from this experience. Low-rise construction, up to five or six stories, generally comprises platform construction with cross walls set perpendicular to one another, and floors placed on top. With this construction method, upper stories are load

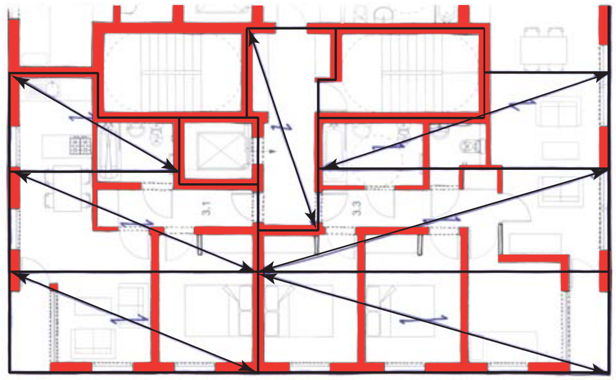

Figure 2. Strategy to resist accidental damage

bearing 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 scale.

1. Fire

   In buildings of solid timber, charring is relied on for structural fire resistance. There is no chemical fire resistance treatment as such. 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 soft timber from various sources. Close grain timber specified on the faces of panels significantly improves fire resistance. For residential units, the firewall separations within apartments should have one-half hour integrity; between apartments, one hour integrity; and between apartments and principle vertical circulation, two hours integrity. The conduits are placed between wall and plasterboard lining, in other examples they have been chased in. Standard PVC conduit was used with no special provision.

2. Robustness

   Panelized 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 the Stadthaus was in the assessment of options to ensure the robustness of tall timber structures. Design research continues in the movement characteristics of these forms. In the UK, there is design guidance developed by the Building Research Establishment (BRE) to prevent catastrophic failure in timber frame construction of up to six stories. This is directly applicable to massive timber construction. There is no EU guidance, at the time of writing, on this subject. Discussions with the Timber Research and Development Association (TRADA) and the Timber Frame Association (TFA) have brought forth as realistic limit state criteria a notional shock load of 7.5kN/m^2 and the removal of a single wall-length or floor panel.

These requirements led 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 typically found in residential layouts by conjecturing alternative load-paths should any component be compromised.

Therefore a policy of "efficient redundancy" was persued. 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.

For the Stadthaus, four different scenarios of structural damage were considered. Adequate alternative load paths were demonstrated following the removal of various panels (see Figure 2).

3. Strength

   The junction of wall with floor and wall below is the system's "weak link."

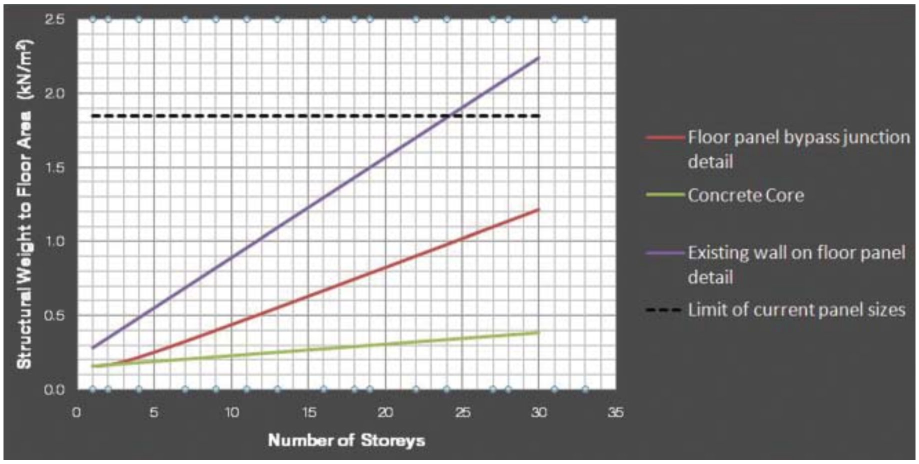

Figure 3. Structural weight/floor area

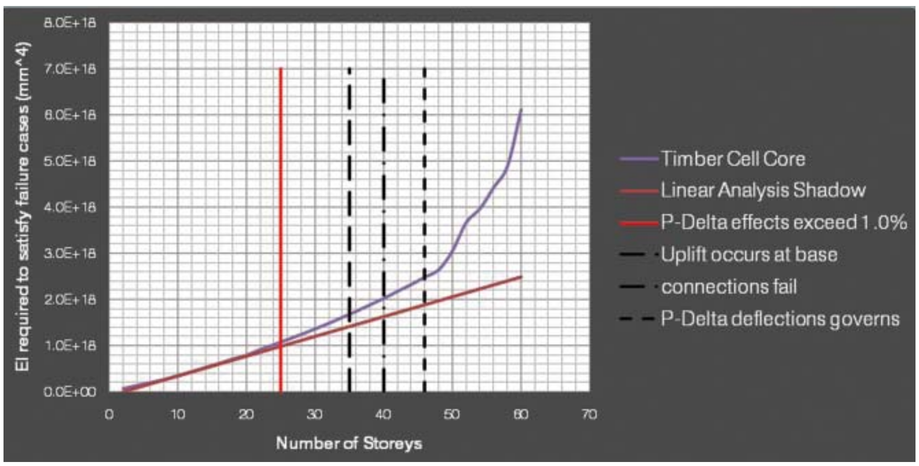

Figure 4. P-delta effects on tall buildings

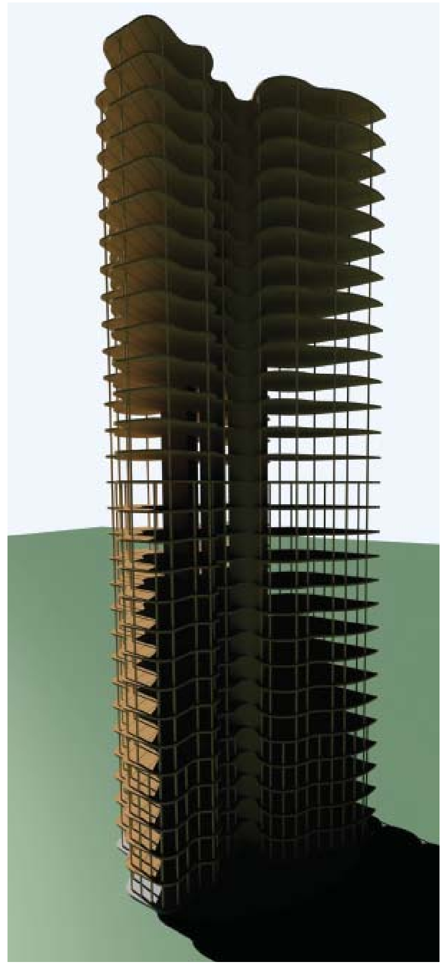

Figure 5. A 30-story timber tower © Lewis Bart Rawson Architects

The end grain strength of the wall panels is 24 N/mm^2. The cross-grain crushing capacity of the floor plate is only 2.7 N/mm^2. Screw or nail arrays at highly loaded points alleviate these concentrations.

4. 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 CLT 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. The thermal coefficient of linear expansion is 34 x10^{-6}, about three times that of steel.

5. 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, two layers of 9 millimeter (0.35 inch) thick plasterboard on each side will achieve Building Regulations Part E requirements: externally, a 10-millimeter (0.39-inch) air gap is needed. Between floors, an acoustic ceiling should be adequate. For stairs and lift cores, double- wall construction is desirable with a 40-millimeter (1.57-inch) air gap.

Method Advantages

The base cost of timber construction is currently about 10 to 20% more than that of a comparable reinforced concrete frame.

However, there are several compensations at construction stage offsetting this cost disparity. Cross-laminated panels arrive by truck in erection sequence. They are lifted into place immediately with no storage, no waste and no wet trades, allowing the site to remain 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. Additionally, the thermal emissivity of an exposed wooden surface is excellent at a value of 0.87. When needed, the timber panels can be cut out with a skill saw and replaced.

Very Tall Buildings: High-rise Design Considerations

As an experiment, a 30-story project is presented to see what a non-cellular CLT building might look like and what problems it would have. This project deliberately reverses the logic of CLT which is to compartmentalize as much as possible and create alternative load paths. 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. Consideration of the elasticity of timber and its relative softness is key to timber use in high–rise building. If the simple platform construction currently being used is unmodified, then a straightforward point block can reach 15 stories with economic wall thicknesses. If bearing points are strengthened locally, then two or three extra stories might be added. An indication of structural weight to floor area provided for increased height is shown in Figure 3.

Techniker have proposed a jointing method taken from packaging design that interleaves wall and floor elements to form continuous vertical load paths down through the building.

Tie and bearing details can be improved in several ways. Hardwood margins could be added. Tower designs would then move into the area shown in Figure 3, where the P-delta effect begins to govern wall thicknesses and hence costs. This is a destabilizing moment equal to the force of gravity multiplied by the horizontal displacement a structure undergoes as a result of a lateral displacement. 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 added improvements will also add to expense. With the materials now in use, heights can reach 25 stories 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. With a Young's modulus of around 12,000 Nmm, CLT is about three times as flexible as reinforced concrete. For a simple hull and core apartment building extra wall thicknesses are in accordance with Figure 4.

Special configurations and details might be deployed to take timber buildings higher or to offer better value by reducing material use. From the early 1960s onwards, a number of engineers in North America, particularly Fazlur Khan, Leslie Robertson and William LeMessurier, began to reform very tall steel tower designs on a rational basis. Concepts such as mega-frames and bundled-tubes were established.

For cellular constructions involving structural perimeter walls the notions of tube and bundled-tube configurations are helpful. Spreading structure out toward an edge of the plan, then completing closed sections within it, maximizes lateral and torsional stiffness. Given the fixed requirements of vertical circulation, there is some flexibility in typical point block types for opening out the external envelope (see Figure 5).

Above 25 stories, 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 (see Figure 6). Detailing can circumvent the problem of cross grain shrinkage at each floor level (see Figure 7). The differential movement of hull and core can be modeled over time, the load transfers can be assessed and allowances made. In summary, the ethos of the material is to use it directly with the most plain of details and construction methods possible. The underlying attitude considers building as a populist, simple, noble activity. There is still much development potential in this approach. ■

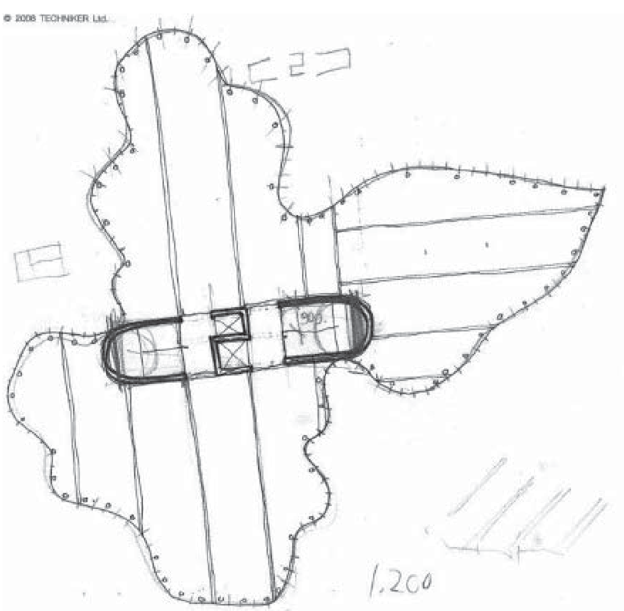

Figure 6. A 30-story tower plan

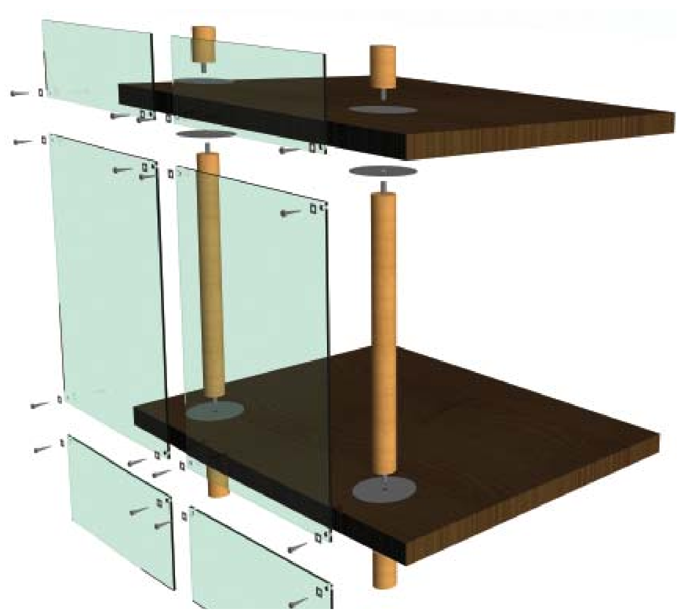

Figure 7. A 30-story tower construction detail