TIMBER MULTI-LEVEL BUILDINGS TO 20 LEVELS BASED ON A CENTRAL CORE OF INTEGRATED CLT PANELS

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Multi-storey, cross-laminated timber, integrated elements

ABSTRACT

This research investigates a new structural system based on a central core of CLT (cross-laminated timber) panels to provide more useful multi-level timber buildings that are taller and with open floor areas. Because pinus radiata is a suitable timber for the manufacture of CLT panels, the system has the potential to add value to planted NZ forests and to earn overseas currency. Timber elements are proposed for the entire building structure - central core, columns, floor beams and floor joists. The vertical timber core is a very large square (or rectangular) hollow section that extends the full height of the building and is the main element for resisting lateral forces. Various aspects of the system are discussed in the paper. An analysis of the structure is reported and the paper concludes that the proposed structural system with CLT elements is suitable for buildings to at least twenty levels.

1 INTRODUCTION

There is a worldwide interest in timber multi-storey buildings due to the environmental advantages of timber construction when compared to buildings in concrete and steel (1). Cross-laminated Timber, or CLT, was developed in the early 1990's and glues and clamps timber planks in alternate layers to form large panels that are up to 16m long x 3m wide x 0.5m thick. The cross-laminating ensures reliable strength and stability. CLT construction has been used successfully for the nine storey Murray Grove Stadhaus building in London and the ten storey Forte building in Melbourne (1, 2). The paper proposes a new type of structural system that utilises CLT for buildings to at least twenty levels. The three main aspects of the structural system that makes it different to the current method of CLT construction are:

1. Integrating CLT panels to form elements that are much larger, and hence stiffer and stronger, than the individual panels
2. Ensuring the vertical CLT panels are placed end on end so gravity loads are only transferred parallel to grain
3. The loads between the vertical joints of the CLT panels are transferred by inter-locking keys that do not rely significantly on steel fixings like nails, screws or bolts.

The proposed structural system, as shown in Figure 1, relies on a central core of integrated CLT panels to support the horizontal loads on the building. The floor plan is similar to a typical reinforced concrete commercial building and has considerably more open spaces than are possible with existing CLT multi-level construction which relies on multiple shear walls. The interior of the central core is suitable for service rooms and the vertical circulation of people and services.

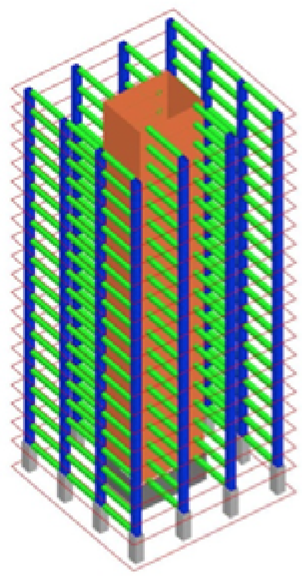

Figure 1: *Isometric of proposed timber structural system for twenty storey building with a rectangular core of integrated CLT panels, and engineered timber columns & floor beams*

The system depends on large cross-laminated timber panels 16m long x 3m wide, being integrated together to form a vertical cantilever with a rectangular hollow cross-section. This very large structural element extends the full height of the building. Hoop or ring beams, made of glulam or LVL, are placed around the core at each floor level. The core panels are screwed to the hoop beams which ensure the core panels are maintained in alignment. The columns and beams are engineered timber, either CLT, LVL or glulam. The proposed timber floor system has timber pole joists and was developed at the University of Auckland and is described in more detail later in the paper. It achieves acoustic insulation, suitable physical performance and is relatively economic. (3).

A joint research project on the behaviour of an integrated CLT panel core under wind loading was carried out with Prof Richard Harris and Tom Reynolds of Bath University (4). Because of this study, the prototype building is considered to be located in a major UK city. The wind loads that are applied to the prototype building for the structural analysis are from Eurocode 1, part 4 (5). The UK is an important potential market for CLT construction because it is popular there. The KLH UK website presents sixteen Education and eight Civic & public buildings that have been completed by KLH in the UK using CLT as the main structural material. Attaching the core to the foundations is explained. This paper does not consider the building system for supporting earthquake loadings, but ductility is provided by the controlled rocking of the CLT core at foundation level and preliminary testing is reported later in the paper. This paper does not investigate the maximum number of storeys that are possible using a cross-laminated integrated core but shows that twenty storeys is feasible.

Figure 2: *Existing commercial building in downtown Auckland with a floor plan of approximately 28m by 28m*

2.0 PROTOTYPE BUILDING

To explain the cross-laminated integrated core system, a prototype building is proposed based on a typical commercial building that is square in plan with 28m sides, similar to the building shown in Figure 2. The proposed arrangement of the core, columns and floor beams is shown in Figure 3. The vertical distance between adjacent floors is taken to be 4.0m, and the overall building height is around 80m.

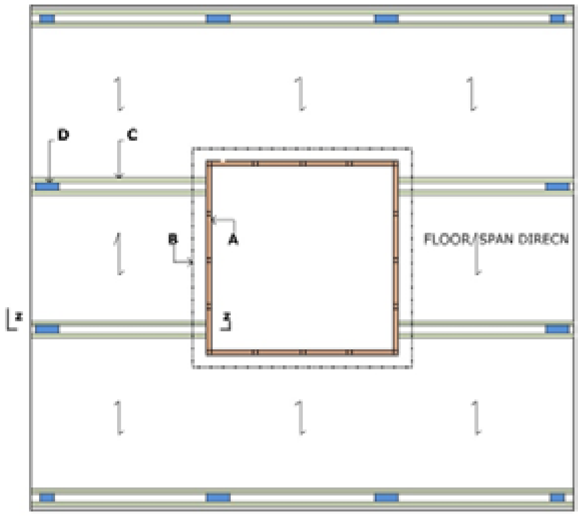

Figure 3: *Plan of structure, A – integrated panel core, B -'hoop' beam at each floor level, C – engineered timber floor beam, D – engineered timber column*

2.1 CLT Panel Core

The integrated panel core of the prototype building has a square hollow section with outer dimensions of 10.8m x 10.8m. It is made up of sixty-four CLT panels that are 16m long and sixteen that are 8m long. The width and thickness of the core panels measure 3m and 320 mm, respectively. Close fitting CLT panels are suited for the central core because they will remain dimensionally stable. Previous investigations found that the most efficient core shape is circular and can potentially support buildings to thirty storeys for a similar volume of timber per square metre of floor area (4). However, a rectangular shaped core is architecturally more useful.

As shown in Figure 4, the core internal walls which are secondary structural elements define the lift wells and the stairwell.

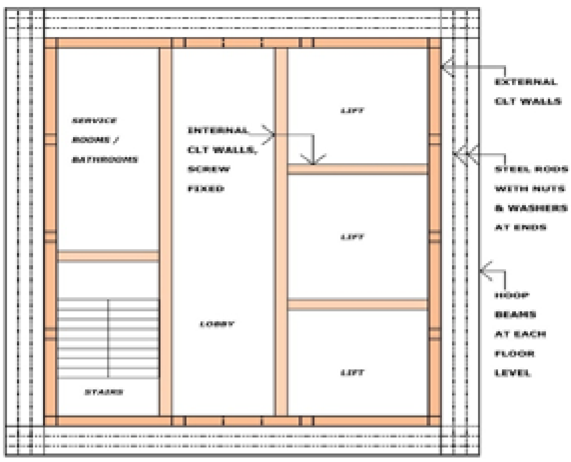

Figure 4: *Plan of internal walls and architectural functions of the integrated panel core. Timber hoop beams are shown including the internal steel rods*

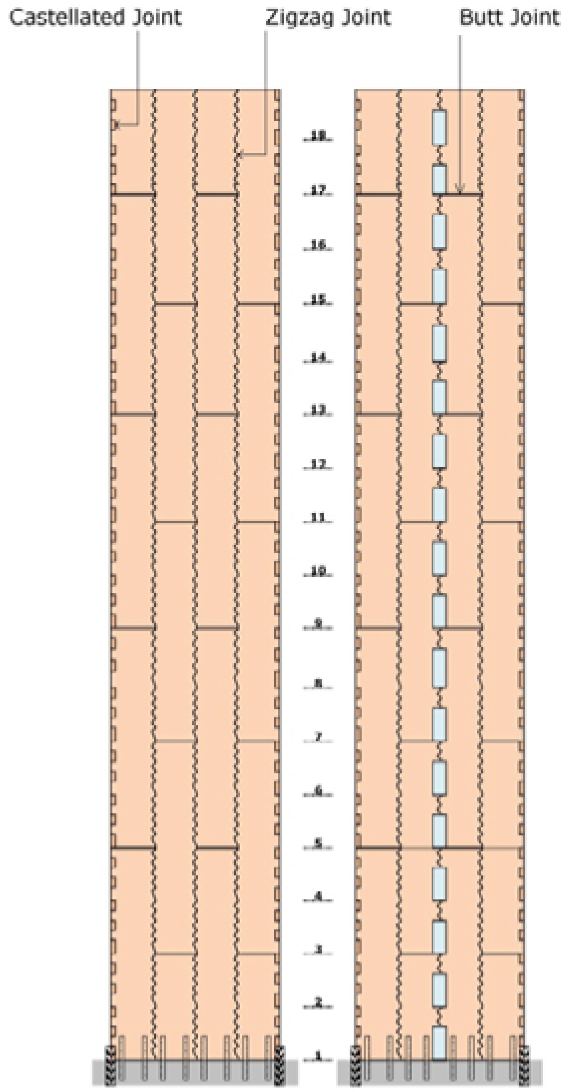

Figure 5: *Eighteen level Integrated Panel Core - Side and End Elevations. Foundation attachments shown – hold down connections, and cantilever steel members (at corners)*

2.1.1 Cross laminated panels

The proposed panel type for the core is taken from the KLH UK Structural Pre-Analysis Tables (6). It is a 320mm thick panel that is described as '8-ss TL: 320 mm (double longitudinal layers on faces and centre of panel). The laminates are 40mm thick and there are six in the vertical or longitudinal direction and two in the horizontal or transverse direction.

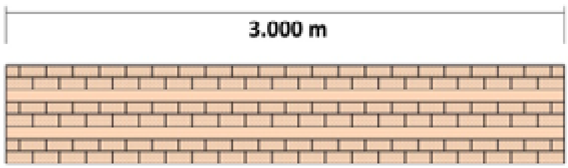

Figure 6: *Horizontal cross-section through CLT panel of core. The vertical scale is increased for clarity. Double longitudinal layers are on the faces and at the centre of the panel*

2.1.2 Joints between CLT panels of the integrated core

To ensure that the panels of the central core act in unity as one structural element, shear forces need to be transferred between the vertical joints of adjacent panels. The solution is to shape the vertical sides of the CLT panels to form 'keys' which mesh with the 'keys' of the adjacent panels. As shown in Figure 5, the corner keys are castellated and the other keys are zigzag. These joints are further illustrated in Figures 7, 8 & 9. Both the castellated and zigzag joints only transfer compression and shear and are simpler, more economical, and less likely to have internal slip than joints with steel fixings. Arranging the CLT panels as a core and the associated panel jointing are new departures for CLT construction and no literature exists on the topic. Part of the next stage of this research is to build and to test these joints. To aid construction and to ensure minimal joint slip, the zigzag joints have an approximately 15 to 20mm gaps between them that are filled with a high strength but low shrinkage grout, such as Sika Grout 215. Also, the castellated joints have 10 to 15mm thick gaps top and bottom that are filled with a drypack grout like Sika Grout 212. Sika Grouts 212 & 215 are described as having the following characteristics (7).

- Positive shrinkage compensation.
- High early age strength development.
- High final strengths. The published compression strength at 28 days is 55 MPa
- Excellent substrate adhesion.
- Adjustable consistency.
- High flow characteristics.

Ply shuttering, which remains permanent, is placed both sides of the zigzag joints to contain the grout when it is pumped into the 15mm approx. wide cavities.

The grout is required to only support compression for which the Sika Grout is suitable and does not need to be an adhesive. Sika 215 grout has proven to have very low viscosity and is used for pumping into rock anchor sleeves. Checking the practicality of pumping this grout for the zigzag joints will be a part of the next phase of this research.

The horizontal joints between the panels transfer compression due to gravity loads in direct butting. Tension forces, which develop in these joints during major Wind & Earthquake events, will be transferred by steel plates both sides of the joints that are attached to the CLT panels by timber rivets.

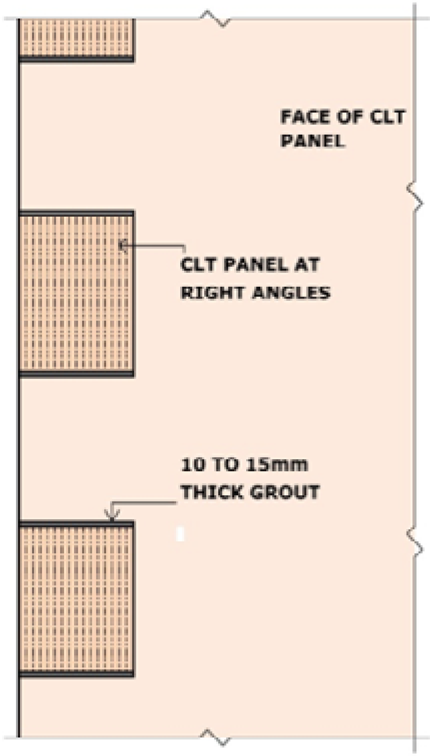

Figure 7: *Elevation of castellated joints at the corners of the central core (the notches' depth is the same as the panel thickness)*

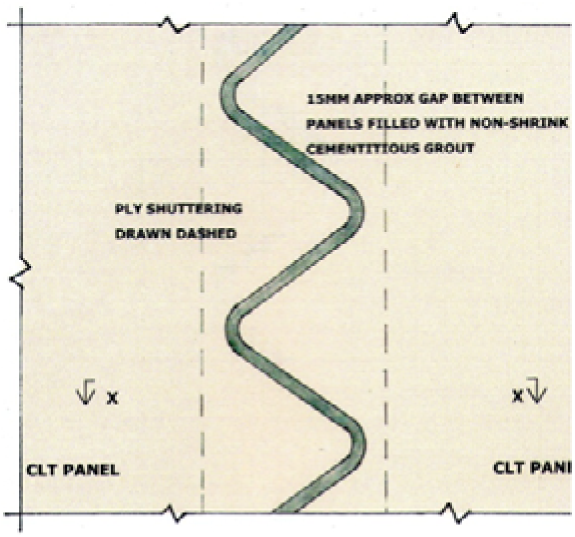

Figure 8: *Elevation of zigzag joint for external walls of the central core*

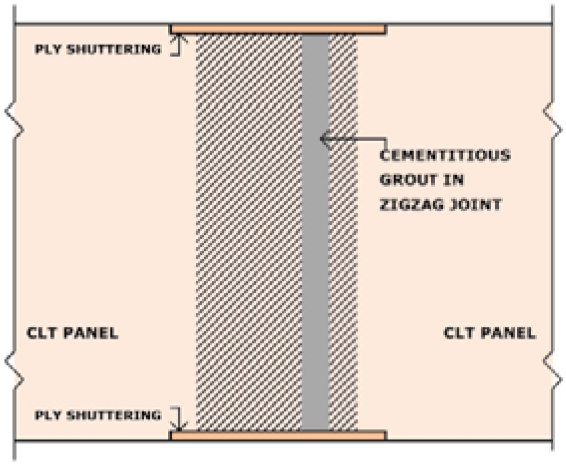

Figure 9: *Section (X-X on figure 8) of zigzag joint for external walls of the central core*

2.1.3 Integrated panel core base attachments

The foundation connection system for the prototype building is designed so that in major earthquake events the integrated panel core can 'rock' and will return to its original location. This connection system is designed to ensure:

- Simple construction using readily available materials
- Sufficient energy dissipation to minimise damage to the main structure during seismic actions
- A defined part of the connection assembly yielding during major seismic actions that, if damaged, can be easily replaced

The proposed connection system for the core to the foundations, as illustrated in Figure 10, consists of pairs of steel 'I' shaped sections at each corner to prevent translation, and steel tie down bars placed regularly around the core to transfer tension forces from the core into the foundations. Typically the core is in compression due to gravity loads but in major wind and earthquake events tension will occur in the core which will induce tension in the tie-down bars. The load path for tension in the core transferring to the foundations is: tension in CLT core » inclined screws (tension) » LVL cleat (compression) » top washer (bending) » top nut (compression) » tie rod (tension) » rod coupler (tension) » foundation bar (tension) » footplate (tension) » foundations. The 'weakest' part of the assembly is the tie down bar to ensure that it will yield before the other components reach their strength limits. The LVL cleat, inclined screws and the top m.s. washer are standard building products. The inclined wood screws are specifically made for connecting large pieces of engineered timber. They are available from a number of manufacturers and have a continuous thread and are self-tapping. The tie rod, rod coupler, foundation anchor bar and footplate are standard items made by Reid Construction Systems (8). The tie down bar and foundation bar are made from ReidBar™ which is a hot rolled 500E reinforcing bar with deformations forming a continuous right hand thread. The load transfer cleat is achieved using a Reid Threaded Connector which is designed to exceed the tensile capacity of the threaded reinforcing bars, and provide connections suitable for seismic conditions. The Reid footplate helps to anchor the foundation rod into the foundations.

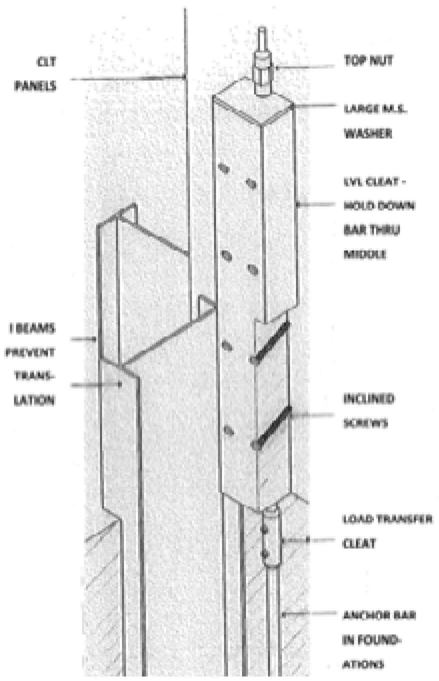

Figure 10: *Diagrammatic isometric of a corner of the core to foundation connection showing pairs of steel members at corners to prevent core translation, and one of the vertical hold-down bar arrangements. (LVL Cleat cut-away for clarity)*

Recently, the proposed rocking system using vertical steel bars and associated coupling nuts of the Reids Construction Systems was studied in a research project by a 'fourth year student at the School of Engineering, University of Auckland' (9). The conclusion of the researcher was 'Overall, the connection has been shown to be feasible, both through specific design and in quasi-static testing, however further investigation is required (9). Dunbar et al tested Pres-Lam technology on CLT panels. A post-tensioned system allowed the wall to uplift under high seismic loads. The hysteretic response is flagged shaped but without the regions of low stiffneess as the high-tensile post-tensioning strands will not plastically deform (10).

2.2 Columns & Beams

The columns are pairs of 1.8m deep * 240mm wide glulam elements screw connected together along one side resulting in a column section of 1.8m * 480mm. The horizontal butt joints are staggered within each column pair and this ensures that any tension stresses that occur can be transferred to the foundations.

Timber can support considerably more compression stress that is parallel to the grain compared to stress that is perpendicular to the grain. For CLT made by KLH, the value in characteristic stress parallel to grain is 24Mpa whereas the characteristic compression stress perpendicular to the grain is only 2.7MPa (11). For the integrated panel core and columns of the prototype building, gravity loads are transferred only parallel to the grain and not perpendicular to the grain as happens with the 'stacked' construction of present CLT buildings. This means the CLT panels for the prototype building in this paper can support 600% more axial compression. This extreme result is from using the KLH 'Technical Characteristics' document. If the stresses for NZ grown pinus radiata published in NZS3603 are used, the improvement is somewhat reduced to around 200% (12).

The floor beams are effectively pairs of 600mm deep x 300mm wide glulam or LVL members. This results in an adequate head height below the beams of 3.1m. The inner ends of the beams are pinned to the integrated panel core but the outer beam ends are fixed to the CLT columns. Fixity is achieved using brackets labelled 'H' in Figure 11.

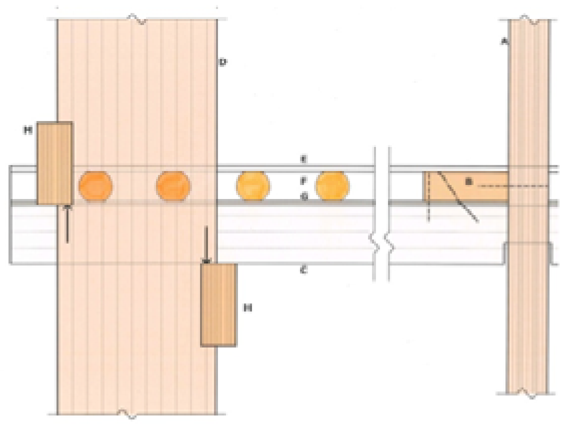

Figure 11: *Floor Beam Elevation (section z on Figure 3), A - core wall, B - 'hoop' beam (Screw fixings to core and floor beams are indicated), C - engineered timber floor beam, D - engineered timber column, E - flooring, F - pole floor joists, G - ceiling, H - corbels to transmit beam moments to the column*

2.3 Timber Floor System

The timber floor as shown in Figure 12 was developed at the University of Auckland. One of the advantages of the floor not having a concrete topping is that it is more flexible and less likely to be damaged when the core 'rocks' in a seismic event. To minimise costs, the joists are timber poles with the top and bottom of each pole shaved to ensure consistent depth. The flooring is sandwich panels with an upper plywood layer, a filling of sand (80%) & sawdust (20%), and a lower plywood layer. The plywood layers are held apart by 70mm deep timber battens at 400mm centres. The floor joist cavity is filled with sound absorbing blanket. A 24mm thick plasterboard ceiling is attached to the joists using spring clips. The floor is suitable for strength, floor vibration and acoustic performance according to the relevant New Zealand building codes (3).

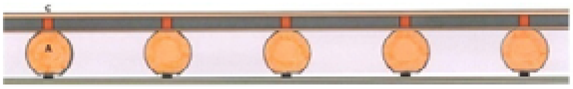

Figure 12: *Transverse section through the proposed floor construction. The joists are poles at 600c/c with sound blanket between them. Above the joists are the flooring panels. Below the joists are the spring clips and plasterboard ceiling.*

2.4 Hoop Beams

The hoop beams as shown in Figures 3 & 4 are engineered timber and are placed around the core at each floor level in the plane of the floor joists. The hoop beams are interconnected by steel rods that are placed in ducts within the beams as shown in Figure 4. The hoop beams have multiple functions including:

- Holding the core panels together and maintaining them in alignment with each other
- Transferring horizontal forces into the central core from both the floor beams and the flooring
- Assist in Howe truss action. It is expected that the core may spontaneously partly behave as a Howe truss under horizontal loading where the hoop beams that are parallel to the horizontal load direction become tension members. Correspondingly, the core walls parallel to the horizontal load would behave as diagonal compression members. If this truss action occurs, and the degree it occurs, will need to be tested for.

3.0 ARCHITECTURE

This research investigates the use of CLT panels, for the main structural elements for buildings to around twenty levels. To date the tallest CLT building, the Forte building in Melbourne, has ten storeys. Currently, CLT construction is stacked wall, floor and roof panels as shown in Figure 13. For each level, single storey wall panels are placed. These are overlain by the floor or roof panels. The panels are considered to perform their function individually and not integrated with a neighbouring panel to form a combined unit. This research proposes to overcome the limitations of the ‘stacked’ approach by integrating CLT panels to form a rectangular hollow core that is much larger, and hence stiffer and stronger, than the individual panels. Because the horizontal loads and a large proportion of the gravity loads are supported by the integrated panel core, the floor areas around the core are free of shear walls and have open floor spaces that are similar to a typical modern reinforced concrete commercial building. The core would contain lifts, stairs, service areas etc. A possible internal arrangement of the core is shown in Figure 4.

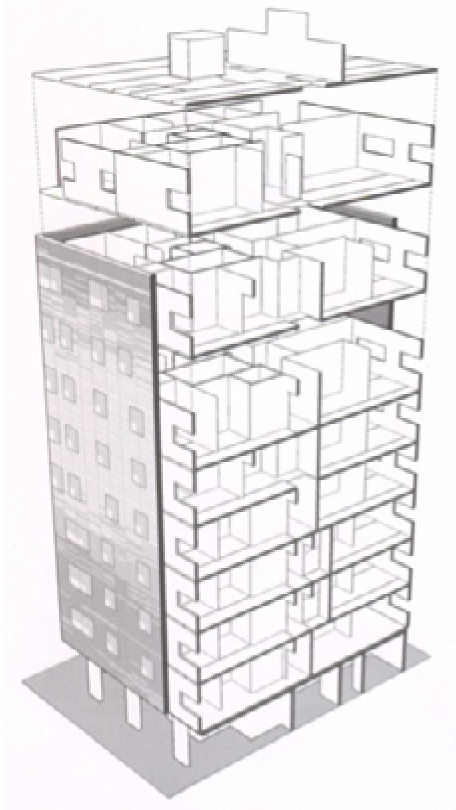

Figure 13: *Isometric of Stadthaus Building. London, showing the close spaced CLT walls*

[image:http://techniker.oi-dev.org/blog/view/a-process-revealed]

3.1 Reinforced Concrete Bottom Storey

At the ground floor, people movements through the core to access lifts will be extensive and 0.8m wide openings, as used above ground floor, are not likely to be sufficient. To accommodate wider openings in the core at ground level, the ground floor structure should be reinforced concrete. The ground floor in reinforced concrete is in effect a podium structure and a foundation for the timber core. Another advantage of reinforced concrete construction for the ground floor is that the floor to floor measurement can be increased above 4m giving a more spacious feel. Also, reinforced concrete for the ground level makes the building less susceptible to large impacts at street level, should any occur.

4.0 FIRE

Possible types of protection for all of the timber structural elements include sprinklers, sacrificial wood layers, plasterboard linings, and clear intumescent paint. The charring rate for CLT panels is 0.67mm/minute for the top layers and 0.76mm/minute for the other layers (11). At this rate, loss of wood is 40mm/ hour, which is the thickness of the panel laminates. This is very similar to the charring rate for pinus radiata in NZS3603 at 0.67mm/minute. Thus, adding an extra 40mm thick outer laminate layer will give an hour of fire protection. Plasterboard systems can be used for fire ratings up to 3 hours and intumescent coatings have fire ratings up to 90 minutes (13). The Architect, to achieve desired surface finishes as economically as possible, will likely combine all of the above four options in various ways.

5.0 STRUCTURAL ANALYSIS

Eurocode 1 is used for determining the loads and load combinations on the prototype building (5,14). The floors' dead and live loads are both taken as 3.0kN/m2. The wind forces, W, on the building are based on a fundamental value of basic wind speed of 23m/s and a site altitude of 100m which is suitable for most large UK cities. The physical properties of the CLT panels are taken from the KLH UK Engineering Brochure (9). An elastic analysis was completed using Multiframe 4D from Bentley Systems (15). In the next part of the research the integrated panel core is to be subjected to a Finite Element Analysis.

5.1 Critical Member Actions

Based on the structural analysis, Table 1 presents for the core, columns and floor beams:

- Critical member actions for the combined load cases from Eurocode 1
- Maximum allowable member actions based on a strength reduction factor, φ of 0.9 (which is typical for engineered timber members)
- Factors of Safety.

Also, Table 1 compares the member actions with their reliable strengths. The member actions are divided by the reliable strength and the results are expressed as a percentage. Thus, the core is at 56% capacity in bending and at 24% capacity for axial compression. The last row in the table adds these two percentages together to ensure they are less than 100% and hence the members are safe. A building taller than twenty levels is possible if the integrated panel core is made with larger plan dimensions. For a core with plan dimensions of 16.5m x 16.5m, around thirty floor levels can theoretically be supported.

Table 1*: actions, reliable strengths, & capacities*

	CLT Core	Columns	Beams
Critical load case	0.9G+1.5W	1.35G+1.5Q +0.9W	1.35G+1.5Q +0.9W
Max BM, M* (kN.m)	167,686	425	432
BM Strength, φMn (kN.m)	301,703	5067	751
Bending capacity utilised (A)	56%	8%	58%
Max C, Nc* (kN)	24,302	10,345	1,396
C Strength, φNnc (kN)	103,012	17,626	5,875
Axial load capacity utilised (B)	24%	59%	24%
A + B < 100%, (C)	80%	67%	82%
Factor of safety, 100 / C (to be > 1.0)	1.25	1.49	1.22

5.2 Building Drift

The elastic analysis indicates that the top of the building moves 105mm horizontally under the serviceability limit state wind forces, or 0.0013 times the roof level height of 80m. The maximum inter-storey sway is 7.6mm, which is 0.17% of the inter-storey height. Allowable inter-storey drifts are not clearly defined in BS EN 1991-1-4:2005. However, the deflection is less than the maximum value of 0.2% that is suggested in AS/NZS1170:2002 for the serviceability wind load (16). Understanding the contributions of joint slip to inter-story drift will be a part of the next research phase. However, there will be some additional inter-storey sway due to joint slippage that has not been accounted for in the elastic analysis. Testing will eventually lead to an understanding of this aspect as well as the damping effects of the non-structural elements of the building. However, the timber member joints are all in direct compression that are considerably stiffer and less likely to slip compared to joints that rely on multiple screw or nail fixings.

6.0 CONCLUSIONS

A worldwide interest in timber multi-storey buildings is expected due to the environmental advantages of timber construction when compared to buildings in concrete and steel. The paper proposes a new type of structural system that utilises CLT for buildings to twenty levels. There are three main aspects of the structural system that makes it different to the current method of CLT construction. The first is to integrate CLT panels to make a strong and stiff central core for resisting the lateral building loads. The second is to ensure that the vertical structural elements are placed end on end so gravity loads are only transferred parallel to grain; and thirdly that vertical edges of the CLT panels are shaped so they transfer both shear and compression into the adjacent panels by inter-locking keys. These joints do not significantly rely on steel fixings like nails, screws or bolts. Hoop beams are placed around the central core at each floor level that hold the CLT panels in position and assist in transferring horizontal building loads into the core. The other major structural elements, the columns and floor beams, are also made of engineered timber. The floor construction is comprised of timber elements with sand ballast to assist acoustic insulation between floors. The floor plan with a central rectangular core and columns at the perimeter is similar to a typical reinforced concrete commercial building. This arrangement has considerably more open spaces than existing CLT multi-level buildings which rely on multiple shear walls. The foundation system for the prototype building is designed so that in earthquake events the integrated panel core can 'rock' and will return to its original location. When the integrated panel core rocks, replaceable vertical hold-down bars between the central core and the foundations yield and absorb earthquake energy which reduces damaging stress levels in the structure. The bottom storey should be reinforced concrete to assist large flows of people to the lift core, allow a larger ceiling height, and to resist any large impacts at ground level. An elastic structural analysis indicates that the main structural members are 'safe' and suitable inter-storey deflections are achieved during major wind events.

The paper concludes that timber buildings with integrated panel cores overcome many of the limitations of the current form of CLT construction. For the major UK cities, the integrated panel core system is suitable for supporting buildings to at least twenty levels.

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