INTEGRATING CROSS-LAMINATED TIMBER PANELS TO CONSTRUCT BUILDINGS TO TWENTY LEVELS

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ABSTRACT

This research involves a new structural system based on CLT (cross-laminated timber) panels to provide taller and more useful timber high-rise buildings. 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 a central core, columns and floor beams. The point of difference compared to CLT high-rise buildings to date is the central core which is comprised of integrated CLT panels. The central core runs the full height of the building and is effectively a very large vertical cantilever with a rectangular hollow section. The integrated panel core is the main element for resisting lateral forces and produces taller building with more open floor areas. Various aspects of the system are discussed in the paper. An analysis of the structure is reported and the paper concludes that the proposed system with CLT elements is suitable for buildings to at least twenty levels.

KEYWORDS: Multi-storey, cross-laminated timber, integrated elements

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 (Waugh et al 2009). 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. The cross-laminating ensures reliable strength and stability. CLT construction has been used successfully for the nine storey Murray Grove Stadthaus building in London and the ten storey Forte building in Melbourne (Waugh et al, 2009). This paper proposes a new type of structural system that utilises CLT for buildings to 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 an individual panel
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 CLT panels are transferred in direct bearing and do not rely on steel fixings like nails, screws or bolts.

The proposed structural system relies on a central core of integrated CLT panels to support the horizontal loads on the building as shown in Figure 1. The central core is made up of large cross-laminated timber panels, many at full size, 16m long * 3m wide that are 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 beams, made of glulam or LVL, are placed around the core at each floor level. The hoop beams are screwed to the core panels and thereby ensure the panels' alignments are maintained. The columns and beams are either LVL or glulam. The resulting 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. The proposed timber floor system, which is described later in the paper, was developed at the University of Auckland and achieves acoustic insulation, suitable physical performance and is relatively economic. (Chapman et al, 2009).

To explain the system a prototype building that is proposed and analysed. The wind loads that are applied to the prototype building for the structural analysis are from Eurocode 1, part 4 (BS EN 1991-1-4:2005). The prototype building is considered to be located in a typical large UK city because CLT construction is popular in the UK. The KLH UK website presents 16no. education and 8no. civic & public buildings that have been completed by KLH in the UK using CLT as the main structural material. The analysis does not include earthquake loading but funding is currently being sort for testing a scale model of an integrated panel core on a shaking table to evaluate the efficiency of the system in seismic events. The paper discusses how the effective core section reduces when tension stresses occurs and the factor of safety of the core under these conditions. Attaching the core to the foundations is explained. The paper does not consider the building system for supporting earthquake loadings, but the core to foundation connections has the advantage of allowing controlled core rocking in an E event. As shown in figures 2, 5 & 6, the joints between the CLT panels of the central core 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.

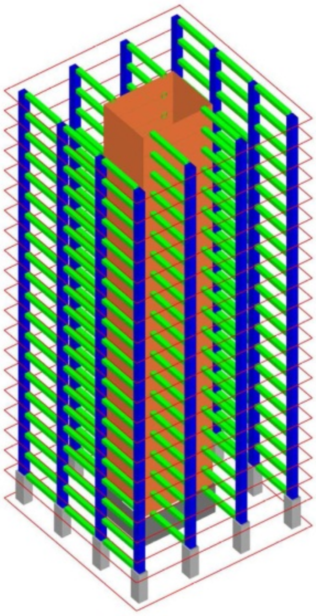

Figure 1: *Isometric of proposed timber structural system for twenty storey building with a rectangular core of integrated CLT panels, glulam columns and floor beams*

Figure 2*: Existing commercial building in downtown Auckland with a floor plan 30m by 30m*

PROTOTYPE BUILDING

A prototype building, similar to that shown in Figure 2 is used to explain the integrated CLT panel core system. It is a typical commercial building that is square in plan with 30m sides. 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.

Integrated Panel Core (IPC)

The integrated panel core, or IPC, of the prototype building has a square section with outer dimensions of 10.8m x 10.8m. It is made up of sixty-three CLT panels that are 16m long and fourteen 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 (chapman, 3013). However, a rectangular shaped core is architecturally more useful.

The integrated panel core is a vertical cantilever with a rectangular hollow section and supports the lateral loads on the building. Stability for the walls of the integrated panel core is provided by the floors, ring beams, and the internal CLT walls of the core. As shown in Figure 14, the internal walls of the core define the lift wells and the stairwell. They are not primary structural elements, and are made of screw fixed CLT panels.

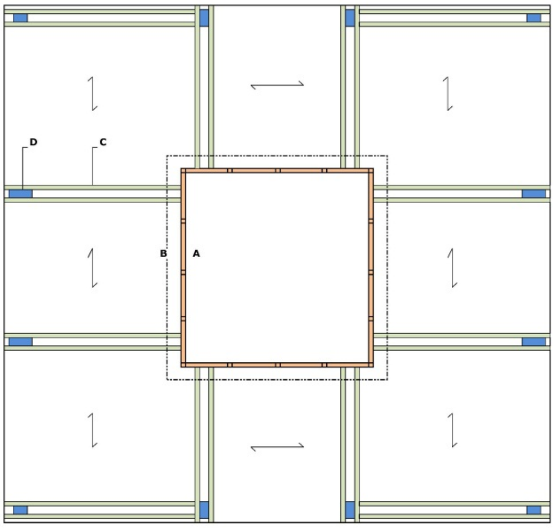

Figure 3: *Plan of structure, A – IPC (integrated panel core), B -'hoop' beam at each floor level, C – engineered timber floor beam, D – engineered timber column, arrows indicate floor joist span*

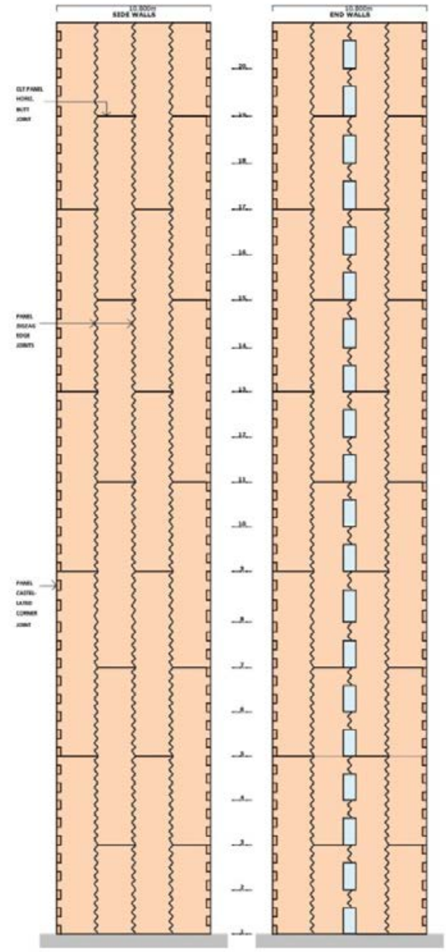

Figure 4: *Twenty level Integrated Panel Core - Side and End Elevations*

Cross laminated panels

The proposed panel core is 280 mm thick with a total of seven laminates that are each 40mm thick. There are four laminates in the vertical or longitudinal direction and three in the horizontal or transverse direction. More laminates could if additional strength or stiffness were needed.

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 for the sides of the CLT panels to be shaped to form ‘keys’ which mesh with the ‘keys’ of the adjacent panels. As shown in figures 4 & 8, the corner keys are castellated and the keys between panels in the same vertical plane are zigzag. 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 15mm gap between them which is filled with a high strength but low shrinkage grout, such as Sika Grout 215. Also, the castellated joints have 10mm thick gaps top and bottom which require filling with a drypack grout like Sika Grout 212. Sika Grouts 212 & 215 are described as having the following characteristics (nzl.sika.com, 2014) - positive shrinkage compensation high early age strength development, high final strengths, excellent substrate adhesion, adjustable consistency and high flow characteristics.

For the zigzag jointing, ply shuttering which remains permanent, is placed both sides of the 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. It does not need to be an adhesive. Sika grout has proven to have very low viscosity and is used for pumping into rock anchor sleeves. The practicality of pumping this grout for the zigzag joints will be a part of the next phase of this research.

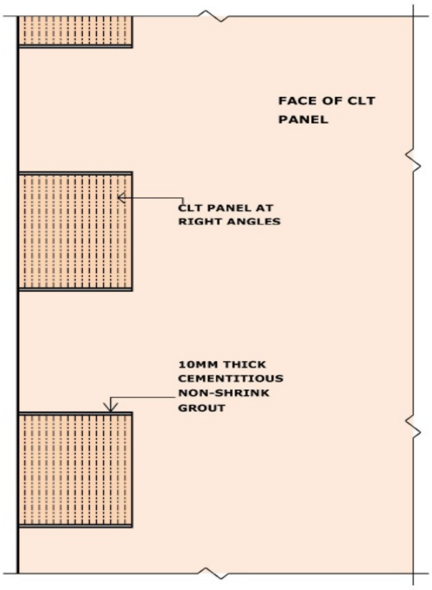

Figure 5: *Elevation of castellated joints at the corners of the central core (the notches’ depth is the same as the panel thickness)*

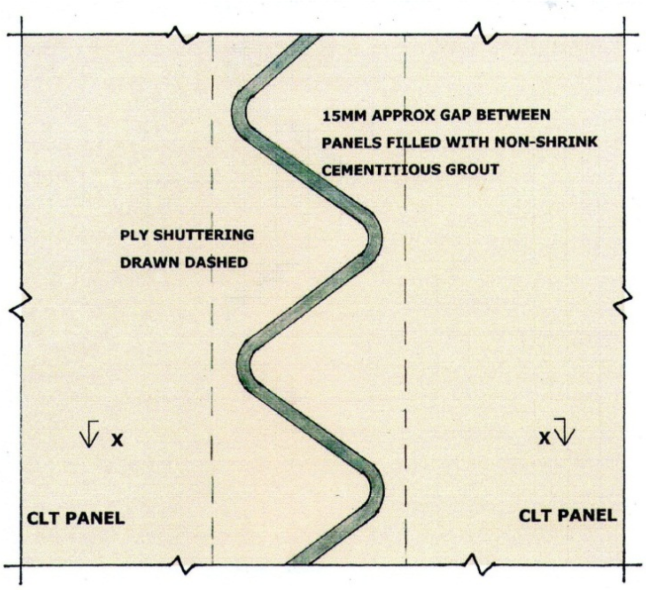

Figure 6: *Elevation of zigzag joint for external walls of the central core*

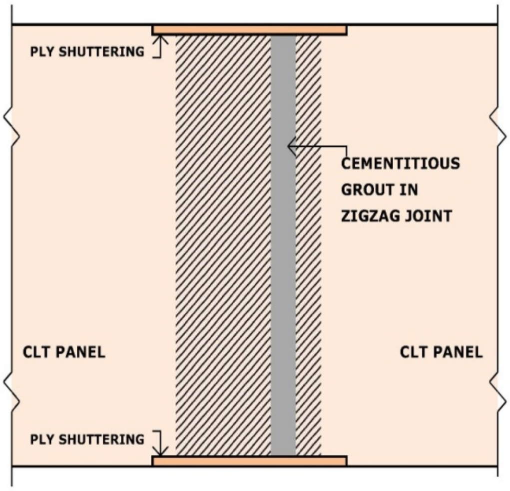

***Figure 7**: Section (X-X) of zigzag joint for external walls of the central core*

Integrated panel core base attachments

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, vertical hold-down bars between the core and the foundations yield and absorb earthquake energy which reduces damaging stress levels in the structure. These rocking systems are currently being studied in depth (Ma, 2010).

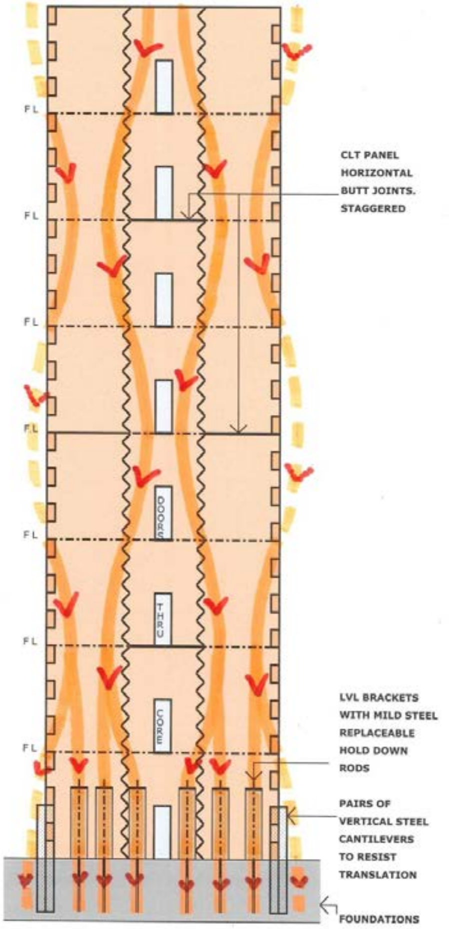

Figure 8: Elevation of IPC showing how tension flows around end joints of CLT panels. The dashed lines indicate tension transferred through the panels at right angles.

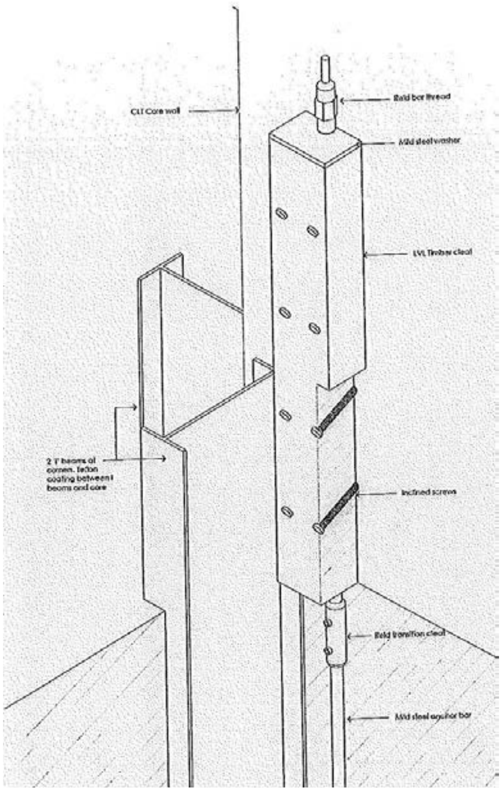

***Figure 9:** Part isometric of IPC foundation connections showing pairs of steel members at corners to prevent IPC translation, and one of the vertical hold-down bars. (Sketch is diagrammatic)*

Initially, the tension in the integrated panel core is transferred by inclined screws to vertical LVL brackets as shown in figures 8 & 9. The force in the LVL bracket is transferred to the foundations by a vertical steel bar that is located in a hole through the middle of the bracket. The steel rod has a large steel washer and a nut at the top, and at the bottom it is screwed into a coupling nut that is also attached to a foundation anchor rod. Each vertical hold down bar will have a dedicated ‘fuse’ region so extension and energy absorption can be controlled. The fuses yield before the other structural elements reach their ultimate limit states. As the fuses yield they absorb seismic energy and after the seismic event any fuses that are damaged can be unscrewed and replaced. The vertical steel bars and associated coupling nuts of the Reids Construction Systems would be suitable for the hold-down arrangement (www.reids.co.nz, 2014).

As shown in figures 8 & 9, pairs of vertical steel cantilevers at each corner of the integrated panel core resist horizontal translation of the core but will allow vertical movement and thus not impede rocking. Where adjacent to the CLT panels, the vertical steel cantilevers may benefit from a coating of PTFE, like Teflon, to assist the rocking by reducing friction.

COLUMNS & BEAMS

The columns are pairs of 1.8m deep * 240mm wide glulam elements connected together along one side resulting in a column section of 1.8m * 480mm. The horizontal butt joints of the glulam elements 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 load that is parallel to the grain compared to load that is perpendicular to the grain. The value in characteristic stress parallel to grain is 24Mpa whereas the characteristic compression stress perpendicular to the grain is only 2.7MPa (www.klhuk.com, 2014). 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.
The floor beams are effectively pairs of 800mm deep * 360mm wide glulam or LVL members. The inner ends of the beams are pinned to the integrated panel core but the outer beam ends are fixed to the CLT columns. This fixity produces frame action when there is bending in the integrated panel core and reduces horizontal drift, and stresses in the core. At the core, the floor beams’ have a loose notch as shown in figure 10 that allows rotation between the beams and the core panels. This allowance for rotation will reduce floor damage when the central core ‘rocks’ in severe seismic events. The hoop beams are screwed to the floor beams, flooring and central core.

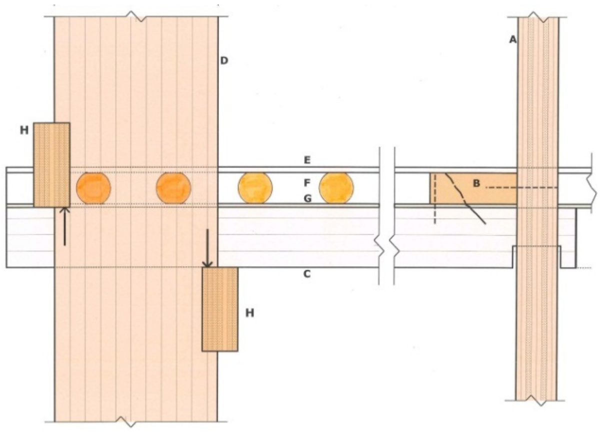

Figure 10: *Floor Beam Elevation, A – IPC (integrated panel core), B - ‘hoop’ beam (Screw fixings to IPC and floor beams are indicated), C – engineered timber floor beam (loose notch indicated at IPC to allow rotation), D – engineered timber column, E – flooring, F – floor joists, G – ceiling, H – corbels to transmit beam moments to the column.*

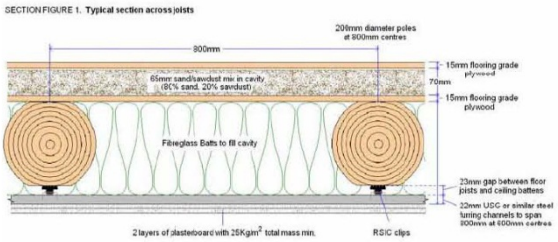

Figure 11: *Transverse section through the proposed floor construction*

The timber floor as shown in figure 11 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 a sandwich of 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 relevant New Zealand building codes (Chapman et al, 2009).

Hoop beams

The hoop beams are shown in figure 3 as engineered timber and as being placed around the core at each floor level in the plane of the floor joists. The beams are held together by steel rods that are placed in ducts within the beams as shown in figure 14. 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
- Reducing the intensity of horizontal bearing pressures on the outer core panels when lateral loads are being transferred into the core from the floor planes

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 12. 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 IPC 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. An internal arrangement of the core is shown in figure 14.

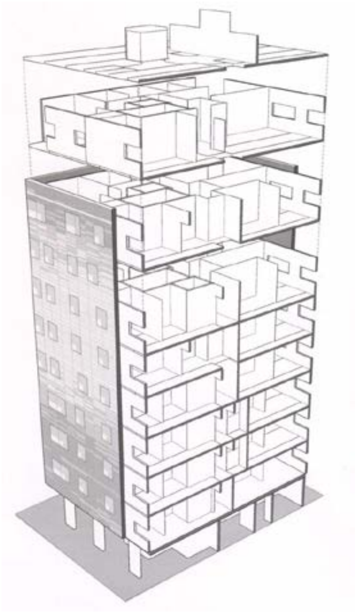

Figure 12: *Isometric of Stadthaus Building. London, showing the closely spaced internal CLT walls*

Reinforced concrete bottom storey

At the ground floor, people movements through the core to access lifts will be extensive and 1.2m 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. Another advantage of reinforced concrete construction for the ground floor is that the floor to floor measurement can be increased above 4.0m giving a more spacious feel. Also, reinforced concrete for the ground level makes the building less susceptible to large impacts at street level.

Fire

For fire protection, it is most likely that the twenty level building would be sprinklered. Possible types of protection for the timber structural elements include 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 (www.klhuk.com, 2014). At this rate, loss of wood is 40mm/ hour, which is the thickness of the panel laminates. 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 (www.gib.co.nz, 2014). The Architect, to achieve desired surface finishes as economically as possible, will likely combine all of the above three options in various ways.

STRUCTURAL ANALYSIS

Eurocode 1 is used for determining the loads on the prototype building. The floors' dead and live loads are taken as 3.3kN/m^2 and 3.0kN/m^2 respectively. 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 were taken from the KLH UK Engineering Brochure (www.klhuk.com, 2014). An elastic analysis using Multiframe 4D from Bentley Systems indicates that the main structural members and associated jointing have reasonable factors of safety (www.bentley.com, 2014). Also, the analysis shows that suitable inter-storey deflections are achieved during major wind events.

Integrated panel core section for 1.35G+1.5Q+0.9W load case

There are only compressive stresses in the core for the 1.35G+1.5Q+0.9W load case. Tension stresses do not occur. Thus, all the vertical laminates of the section are acting and supporting the compression...

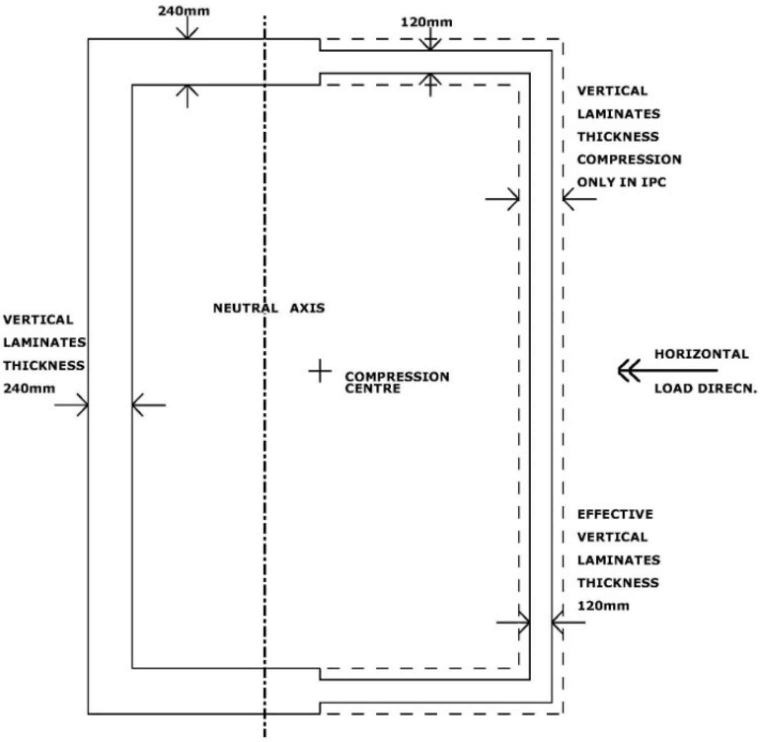

Figure 13: *Effective IPC section when tension stresses occur*

Integrated panel core section for 1.35G+1.5W load case

For the 1.35G+1.5W load case tension stresses up to 6.6 mPa occur in the windward side of the core. The value of the maximum compressive stress in the lee side of the core is higher at 15.6 mPa. Tension cannot be transferred through the horizontal or end butt joints of the CLT panels. As shown in figure 4, the end butt joints of the CLT panels are staggered which results in half the section being available when the resultant stresses are tensile. Thus, when the vertical stress in the integrated panel core is tensile, 50% of the vertical laminates of the core section are available.
A slightly conservative approach to the structural analysis when tensile stresses occur in the integrated panel core is to assume that for the lee half of the core the resultant stresses are compressive and all the vertical laminates are acting; and for the windward half of the core the resultant stresses are tensile and half the vertical laminates are available. This is shown in figure 13. Where the resultant stresses are tension, the available thickness of vertical laminates for structural analysis is effectively reduced from 240mm to 120mm.

Critical member actions in Integrated Panel Core, Columns & Beams

Table 1 presents:

- Critical member actions for the combined load cases from Eurocode 1
- Maximum allowable member actions based on a strength reduction factor, ϕ of 0.85
- Factors of Safety.

The Factors of Safety in the table are calculated using the formula $1/((M^*/\phi\, Mn) + (Nc^*/\phi Nnc))$. The factor of safety of the central integrated panel core is around 1.27. For the values in table 1, the building forces are increased by around 35% and the nominal member strengths are reduced by 15%. The core factor of safety when the unfactored loads and the nominal member strengths are used is considerably higher at around 2.0. A building taller than twenty levels is possible if the integrated panel core is made with larger plan dimensions. Also, the core could be made stiffer and stronger if additional vertical laminates are included in the CLT panels.

Table1: Material properties, reliable strengths, & actions

	CLT Core	Columns	Beams
Critical load case	1.35G+1.5W	1.35G+1.5Q+0.9W	1.35G+1.5Q+0.9W
E (MPa)	12,000	12,000	12,000
BM Stress, $f_{m,k}$ (MPa)	23.0	23.0	23.0
Max BM, M* (kN.m)	176,364	425	432
BM Strength, ϕMn (kN.m)	410,061	5067	751
C Stress, $f_{c,0,k}$ (MPa)	24.0	24.0	24.0
Max C, N_c* (kN)	36,546	10345	1396
C Strength, ϕN_{nc} (kN)	103,012	17626	5875
Factor of Safety	1.27	1.49	1.22

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 0.19% of the inter-storey height. This inter-storey drift is just under the suggested maximum allowable value of 0.2% in AS/NZS1170:2002. There may be some additional inter-storey sway due to joint slippage that has not been accounted for in the elastic analysis. However, the timber member joints are all in direct compression and are considerably stiffer and less likely to slip compared to joints that rely on multiple screw or nail fixings. A factor which reduces inter-storey drift is the damping effects of the internal walls within the central core as shown in figure 14. It is intended to test for these secondary effects in the next phase of this research.

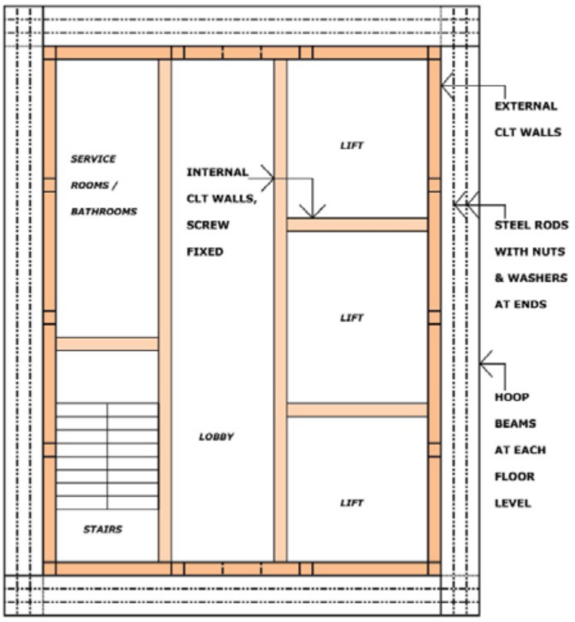

Figure 14: *Plan of architectural functions of the integrated panel core. Timber hoop beams are shown including the internal steel rods.*

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 the integrating of 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 the vertical edges of the CLT panels are shaped so they transfer both shear and compression into the adjacent panels by direct butting action. These joints do not 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 made of glulam or LVL. The floor construction is comprised of timber elements with sand ballast to assist acoustic insulation. 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 closely spaced shear walls. Typically, for the core and columns the stresses are compressive. For a major wind event in a typical large UK city, tension stresses up to 6mPa occur in the integrated panel core and these stresses can be supported and safely transferred into the foundations. The next three phases of this research will be testing the zigzag and castellated jointing, a finite element analysis of the core, and earthquake shake table testing. 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 IPC 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 analysis indicates that the main structural members and associated jointing have reasonable factors of safety for a major wind event in a major UK city. Also, the analysis shows that suitable inter-storey deflections are achieved. For more building strength and stiffness, the core could be made with larger plan dimensions or more layers of vertical laminates could be included in the CLT panels.The paper concludes that cores of integrated CLT panels will overcome many of the limitations of the current form of CLT construction and are suitable for supporting buildings to at least twenty levels.

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