

Connections between CLT elements and future challenges for CLT in practice

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Summary

Since its launch over 15 years ago cross laminated timber (CLT) has gained widespread use with production capacity in central Europe now reaching approximately 600,000m³ per year and worldwide production approximately 700,000m³ [1].

Use of CLT in the UK has seen a rapid increase over the last 10 years with several large school buildings of 10,000m² gross internal floor area and large-scale residential building buildings up to 8-storeys having been delivered. The signs are that this increased use of CLT is set to continue.

However, despite its widespread use, engineers in the UK still face several challenges when designing and delivering CLT buildings such as:

- inefficiencies in the CLT procurement process
- lack of detailed CLT design guidance
- insufficient or inconsistent manufacturers technical data for connections (screws & brackets)

The following paper seeks to highlight these challenges by describing typical UK practice used to deliver CLT buildings.

1. Introduction

Cross laminated timber is manufactured using generally Spruce planks that are glued together in alternating transverse and longitudinal layers. The resultant solid timber panels can be manufactured in thicknesses ranging from 60mm to 300mm and panel sizes up to 2.95m wide x 16.50m long. The panels are manufactured and pre-cut (forming all joints & openings) in the factory to provide an offsite/prefabricated building structure. The prefabricated panels are delivered to site flat-packed (to optimise transport efficiency) and erected by specially trained erection teams. All

panel connections are formed on site, typically using nails and self-drilling screws. There is no pre-drilling of the panel connections unless the connection is to be left as exposed as a feature of the building finishes.

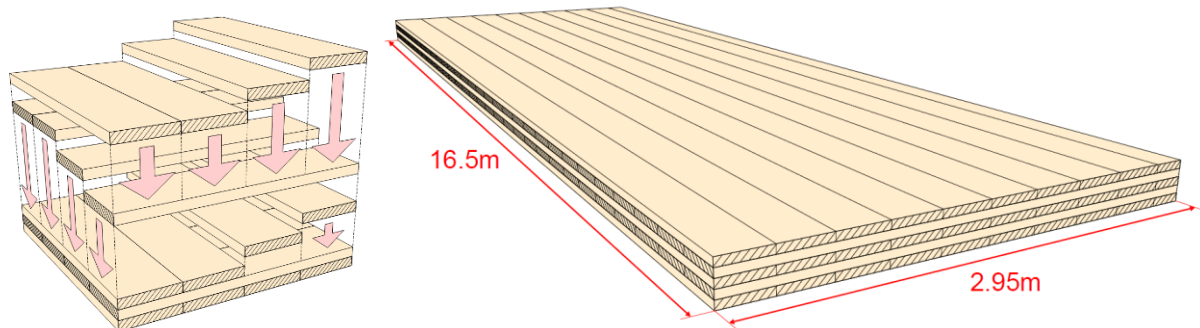


Fig. 1 Cross Laminated Timber

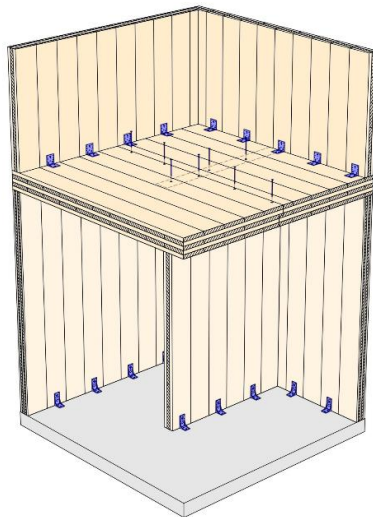


Fig. 2 Platform construction illustration.

Platform construction is the term used to describe the method of ‘stacked’ construction used in most modern multi-storey timber structures. Floor panels bear on top of the wall panels and subsequent wall panels are then erected directly on top of the floor panels. The panels are fixed together using a combination of screwed half lap joints and proprietary metal brackets (Fig. 2). These are described in more detail in the following sections.

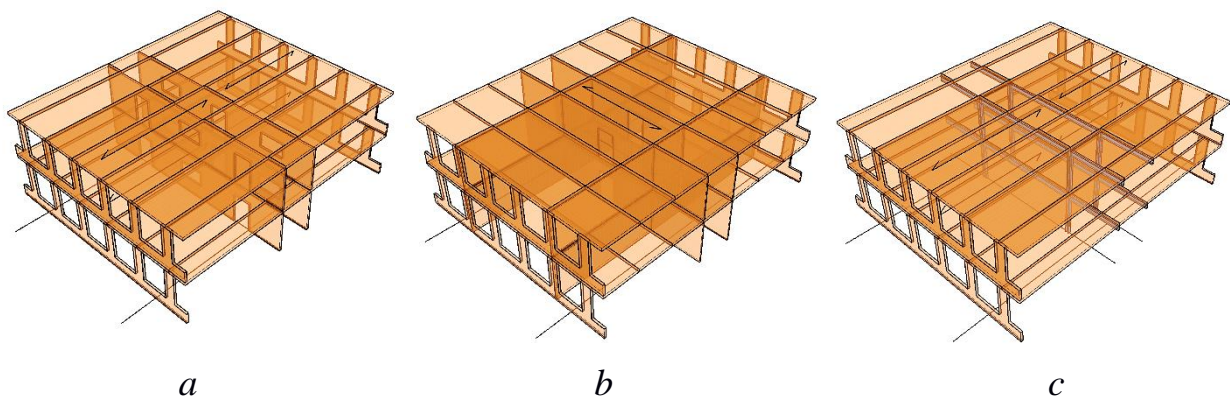


Fig. 3 Illustration of 3 different CLT structure types

CLT buildings can typically be sub-divided into three different structural forms:

- a. Crosswall
- b. Loadbearing façade/corridors
- c. Hybrid (CLT/steel frame, CLT/glulam frame)

2. Design & procurement of a CLT building (typical UK practice) – the challenges

To begin the structural design of a CLT building requires the specific material and structural properties to be known. This is obtained from the product technical data produced by the CLT manufacturer (typically a European Technical Approval document). However, unlike precast concrete or structural steelwork, there is variation in the panel properties and structural performance across the different manufacturers. There has been some collaboration by some of the CLT manufacturers to ‘standardise’ overall panel thickness, which is helpful to the engineer. However, even considering this element of standardisation, there are still variations in the panel performances due to:

1. Variation in the overall panel thicknesses produced by a selection of different CLT manufacturers (Table 1)
2. Variation in the board thicknesses within the same panel thickness produced by two different CLT manufacturers (Fig. 4)
3. Variation in the material properties of a selection of different CLT manufacturers (from manufacturer’s ETA documents) (Table 2).

Table 1 Panel thicknesses from main CLT manufacturers.

Manufacturer	Panel overall thicknesses (mm)													
KLH	60	78	--	90	95	100	108	117	120	125	140	145	--	162
Binderholz	60	--	80	90	--	100	--	--	120	--	140	--	160	--
MMK	60	--	80	90	--	100	--	--	120	--	140	--	160	--
Stora Enso	60	--	80	90	--	100	--	--	120	--	140	--	160	--

Manufacturer	Panel overall thicknesses (mm)													
KLH	180	182	200	201	208	--	226	230	--	248	260	280	300	320
Binderholz	180	--	200	--	--	--	--	--	--	--	--	--	--	--
MMK	180	--	200	--	--	220	--	--	240	--	260	280	--	--
Stora Enso	180	--	200	--	--	220	--	--	240	--	260	280	300	320

The recently published EN 16351:2015 [2] which sets-out minimum standards for CLT production may help to reduce the differences in the panel performance properties. However, currently this variation between CLT manufacturers creates a problem for the engineer designing a CLT building as it means a CLT manufacturer must first be selected in order to commence the design of the CLT structure and confirm the panel thicknesses.

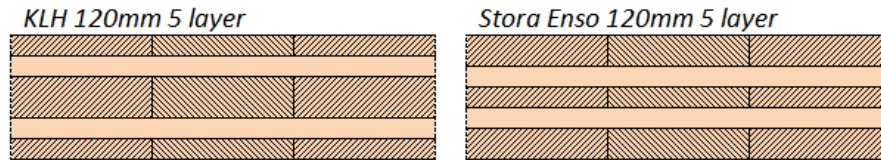


Fig. 4 Cross sections of two CLT panels with the same overall thickness from different manufacturers.

Table 2 Performance properties from main CLT manufacturers for panels made with C24 boards.

MANUFACTURER		Binderholz	KLH	MMK	Stora Enso
Density (kg/m^3)	ρ_{mean}	480	550	480	500
Actions perpendicular to the panel (N/mm^2)					
Modulus of Elasticity	$E_{0,\text{mean}}$	11000	12000	11600	12500
	$E_{0,05}$	7400	9500	7772	7400
	$E_{90,\text{mean}}$	370			
Shear Modulus	G_{mean}	690	690	650	690
	$G_{R,\text{mean}}$	50			
Bending Strength	$f_{m,k}$	24	24	24	26
Tensile Strength	$f_{t,90,k}$	0.4	0.12	0.12	0.12
Compressive Strength	$f_{c,90,k}$	2.5	2.7	2.5	2.5
Shear Strength	$f_{v,k}$	2.5	2.7	2.5	4
	$f_{R,v,k}$	0.7	1.5	1.1	1.25
Actions in plane of the panel (N/mm^2)					
Modulus of Elasticity	$E_{0,\text{mean}}$	11000	12000	11600	12500
	$E_{0,05}$	7400	9500	7772	7400
	$E_{90,\text{mean}}$	370			
Shear Modulus	G_{mean}	250	250	250	460
Bending Strength	$f_{m,k}$	24	23	24	24
Tensile Strength	$f_{t,0,k}$	14	16.5	14	14
Compressive Strength	$f_{c,0,k}$	21	24	21	21
Shear Strength	$f_{v,k}$	2.5	5.2	5	2.5

This variation also creates inefficiencies and challenges in the procurement process for a CLT building which in the UK typically comprises fast track ‘Design & Build’ procurement approach whereby the main contractor will tender the CLT design (based on a preliminary design of the CLT structure) in order to select the CLT supplier. This means the engineer must either adopt a generic, ‘loose fit’, design approach to produce a preliminary design or produce three different CLT structure designs for three different CLT manufacturers. Following selection of the CLT manufacturer the final design (or re-design) of the CLT structure can be completed. Whichever method is adopted, the process is inefficient and puts pressure on the design process. This process is illustrated in the simplified flow diagram below (Fig. 5).

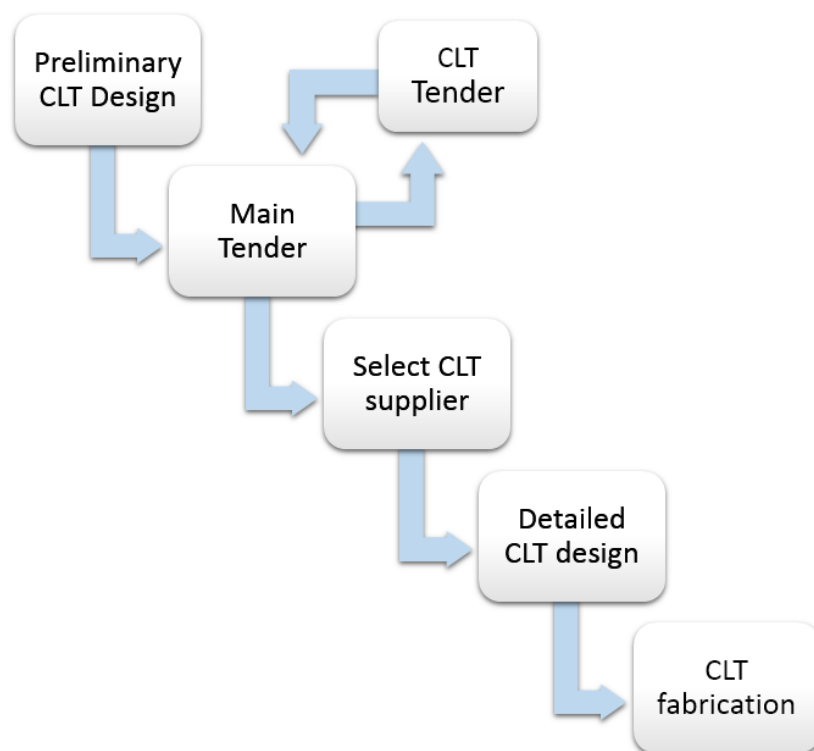


Fig. 5 CLT procurement and design process – typical UK project.

3. CLT Connection types – typical UK practice

3.1 Overview of typical CLT platform connector types

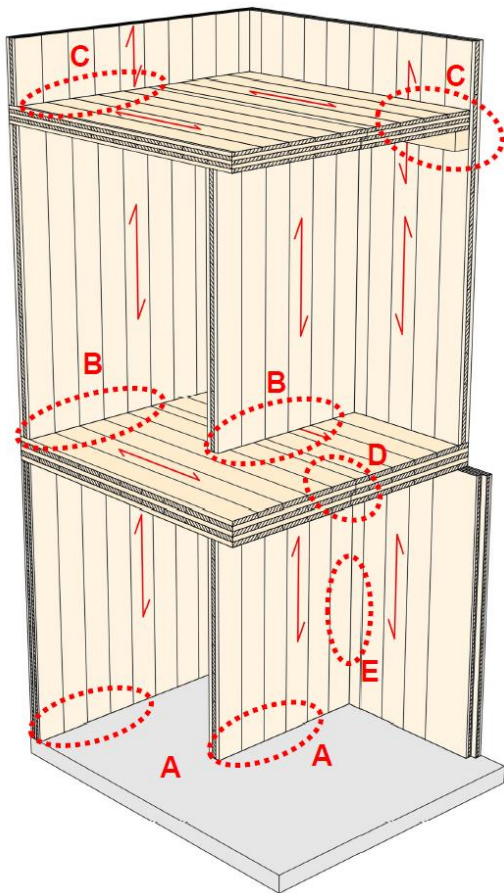
Typical CLT platform construction depends on the connections of all the individual 2-dimensional panels to form a 3-dimensional, stable structure. Figure 6 shows the main types of joints & connections used on a typical UK CLT project.

The typical connectors (Fig. 7) used in CLT construction can be categorised into two types:

1. Screws
2. Proprietary metal brackets/3-dimensional nail plates (3DNP)

Both types of connectors have many different sub-types specifically designed for different applications which have to be taken into account for an efficient design.

The engineer has to commence the design of CLT connections by firstly selecting the connector type, and more specifically the manufacturer. The reason the latter is important is the fact that (similar to CLT manufacturers) there are differences in technical data and load capacities across the different connector manufacturers.



- A. CLT wall to concrete connection
- B. CLT wall to CLT floor connection
- C. Roof parapet connection
- D. Half lap
- E. Wall junction

Fig. 6 Typical joints/connections of a CLT platform structure.

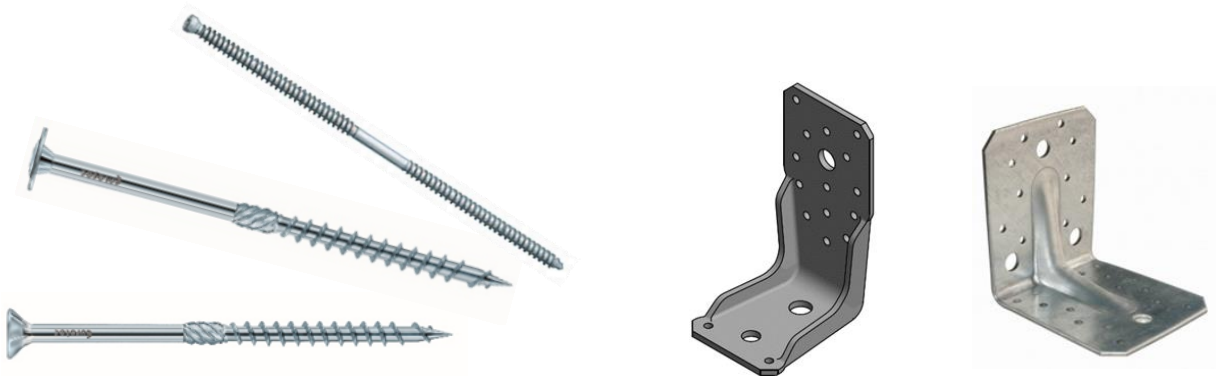


Fig. 7 Typical screw & bracket types.

3.2 CLT wall to Concrete connection (Type A)

CLT wall panels are connected to the concrete foundation using 3DNP. These are fixed down to the concrete foundation with a post-drilled mechanical anchor, and fixed to the base of the CLT wall panels using nails and/or screws. The wall panels are located on top of levelling shims to account for the slab level construction tolerances. Once panels are installed and fixed the gap between the bottoms of wall panels and the concrete slab are filled with non-shrink cementitious grout to ensure the structure loading is transferred to foundations as uniformly distributed line loads.

In this type of connection the main forces the connections are required to resist are:

- In plane shear loads (e.g. stability wall)
- Out of plane shear loads (e.g. external wall)
- Uplift tension (e.g. stability wall)
- In and out of plane shear loads (due to ‘disproportionate collapse’ load case)

There is a range of different type of connectors to solve this connection (Fig. 8), each with different performance values. Three of the most typical 3DNP are:

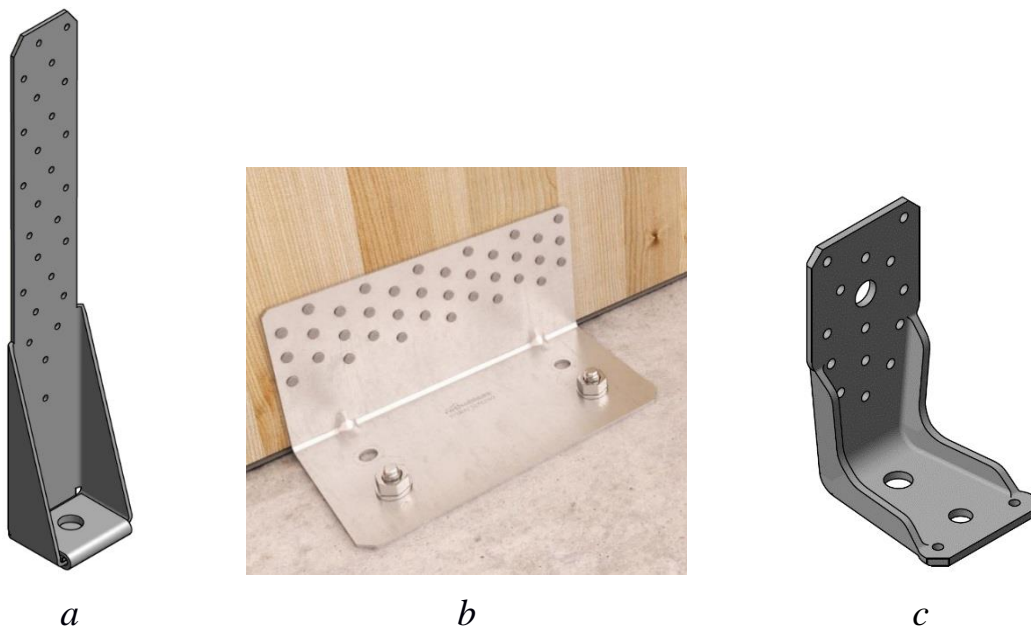


Fig. 8 Typical CLT wall to concrete brackets: a) Hold down, b) TITAN, c) AKR135.

1. Hold downs (Fig. 8a) transfer high tension/uplift loads down to the foundations. Usually the limiting factor is the steel (bracket strength) and the anchor into the concrete (concrete pull-out failure). Due to the high load capacity a reduced number of connectors may be required to take the uplift load. However, this can result in concentrated loads/reactions causing problems for the design of the supporting foundations and a reduced degree of redundancy in the connection.

2. Shear brackets like the TITAN from Rothoblaas (Fig. 5b) provide a significant shear load capacity if they are fully nailed. The shear load transfer creates a tension load to be resisted by the anchor. This makes the steel and/or the concrete anchor the limiting factor. A thick washer can be added to resist tension loads. However the use of the washer creates a lever arm effect in the bottom flange thereby potentially increasing (by a factor of up to 2.0) the uplift load to be resisted by the anchor.
3. Post bases like the AKR135 from Simpson Strong-Tie (Fig. 5c) have stiffening flanges to transfer the uplift without increasing the load on the anchor and can transfer shear loads unlike the large hold downs. The maximum capacities are lower than the previous two options increasing the number of connectors needed per wall length. Thus the loads are distributed along several brackets. This type of connector is sensitive to the edge spacing of the fixings in the bottom of the CLT wall panel (i.e. in the case of uplift). It is therefore important to carefully control construction tolerances of the concrete slab levels.



Fig. 9 Typical CLT wall to concrete connection with grouted gap at wall base.

Not all the connectors described can transfer all the load directions required. In such cases different connector types need to be mixed in one wall to solve the connection. There are two main options: The use of hold downs at either end of the wall combined with shear brackets at the centre, or the use of the smaller post base connectors which are able to take tension and shear loads distributed along the whole length of the wall. The latter is the usual solution with brackets typically spaced at 300-500mm centres as shown in the figure below.

3.3 CLT wall to CLT floor to wall connection (Type B)

This is the typical connection in platform construction where CLT floor slabs are supported on top of the walls and the next wall is located on top of the slab. Some of the benefits of this method are the ease of installation, the accommodation of installation and fabrication tolerances and the direct load path to the horizontal shear loads between floor slabs and walls. One of the disadvantages is that in taller buildings, where vertical loads are higher, the compression perpendicular to the grain on the floor slab tends to be the limiting factor.

The range of loads this type of joint needs to transfer is the same as those detailed in the previous connection, type A.

Connection type B can be subdivided into two:

1. Slab to wall: CLT subcontractors prefer to fix the floor slabs down to the top of the wall below using structural washer head screws partially threaded (Fig. 10a). They provide shear capacity and clamp the panels together when the threaded part is on the pointside member. However if there is a need to transfer higher loads and/or the panel below has 5 layers with the screw going into the end grain it may be necessary to use countersunk screws installed at an angle to the grain. If that solution does not meet the requirements, a 3DNP can be fixed from the wall to the slab soffit. However, this creates difficulties and inefficiencies during installation and it should be avoided if possible.
2. Wall to slab: The most frequent solution for this connection is a 3DNP partially or fully nailed to both wall and floor panels. There are many different types of sizes and load directions that these can resist. However they can be divided in two main groups; i) larger brackets which only transfer shear loads (Fig. 10b) or ii) smaller brackets with shear and tension performance capacities (Fig. 10c). On the one hand, the latter type spread the load over a greater length of the wall as they are typically located at 300mm to 500mm centres (Fig. 11). If partially nailed brackets are specified, it should be clearly marked and checked later during installation which holes need to be nailed as it is critical to achieve the specified structural performance. On the other hand, if the wall is subjected to high loads and bigger shear brackets are needed, most likely a bespoke connection to take the uplift generated by that shear load will need to be designed.

Countersunk



Washerhead



a

b

c

Fig. 10 a) Structural timber screws (Eurotec), b) TITAN bracket (Rothoblaas) and c) ABR105 bracket (Simpson Strong-Tie).



Fig. 11 Typical CLT wall to slab connection showing ABR105 brackets.

There are other factors to take into account when designing this connection. For example, when the connection is on the external walls the brackets can only be fixed from the inside whereas when the connection is on internal walls the brackets can be staggered to either side of the wall (Fig. 12). Also it is important to account for the architectural finishes and whether or not they will cover the connector if the CLT wall is exposed.

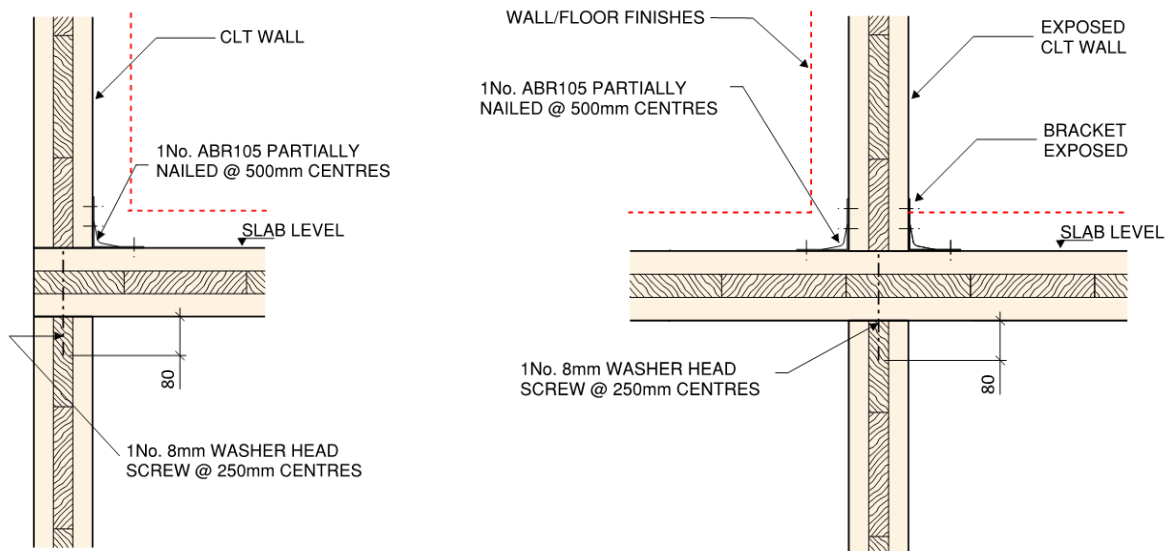


Fig. 12 Typical detail of internal and external CLT wall to CLT floor.

3.4 Half laps and wall junctions (Types D & E)

These connections are made to notionally tie all panels together and typically use washerhead-type screws installed through the half lap joint at 250mm centres. They are also used in the design as disproportionate collapse design to NA to BS EN 1991-1-7 [3], or to tie together the panels when using the notional removal approach.

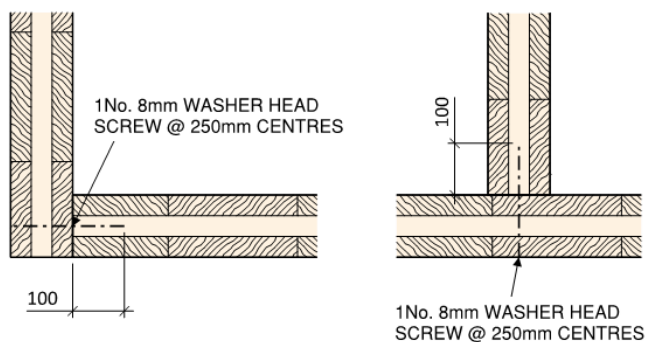


Fig. 13 Typical wall junction detail.

The wall to wall junctions are usually formed with washer head screws to simply clamp the panels together (Fig. 13). If there is a need to transfer axial loads by the screw, countersunk screws may be required installed at an angle to avoid going into end grain. However if they need to transfer a higher load the connection can be solved as the wall to slab connection using 3DNP.

When designing half laps to joint two floor slab panels (Fig. 14) there is a conflict between two design criteria: i) minimum timber wastage and ii) maximum edge distance. The width of the half lap should be kept to a minimum to optimise timber wastage. This is when an accurate minimum edge distance of a screwed connection on CLT (this is not well documented in ETAs or other relevant timber standards) plays a significant role. For example, a 50mm wide half lap (25mm edge distance) over the two long edges of a 12.5m long x 2.4m wide panel represents a timber wastage of more than 2% in volume.

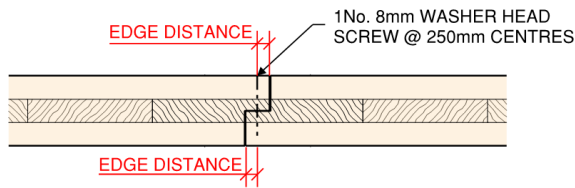


Fig. 14 Typical half lap detail.

If the half lap has been designed to transfer loads across the panel joint, it should be clearly specified in the drawings as a special connection detail. Also it is good practice to check it has been included in the production drawings and on-site checks during CLT erection should check the detail has been fixed as specified. A reduction of the half lap or the incorrect installation on site could lead to the failure of the connection.

3.5 Roof parapet connections (Type C)

Unless the roof is used as a terrace, the main action the parapet connection to the roof slab has to transfer is the horizontal wind load. Depending on the height and/or the wind pressures there are different approaches to solve the joint. From lower to higher demand they are:

1. If the parapet height is not significant and/or most of the parapet height is going to be covered by the roof finishes, the solution of a small ribbed 3DNP and a screw through the roof slab described above for the external wall to floor to wall connection may be enough to transfer the moment and shear actions (Fig. 15a).
2. The second option uses the same detail as the first one but adding a nail plate in the external face (Fig. 15b). This option has the disadvantages that the connection has to transfer a moment created by the wind load as option 1 and that the nail plate has to be fixed to the external face which sometimes is not possible depending on the installation approach chosen by the CLT contractor.
3. The third option shows a change in the panel layout. The roof slab is not supported on top of the wall. Instead it has the wall running through with the slab supported by a CLT strip or timber member screwed in the wall (Fig. 15c). It can be beneficial when the parapet heights are significant or the wind causes a moment in the junction which is too high for option 2 but can be taken by the wall as a cantilever member. The installation of the roof slab of this detail can be more complicated.

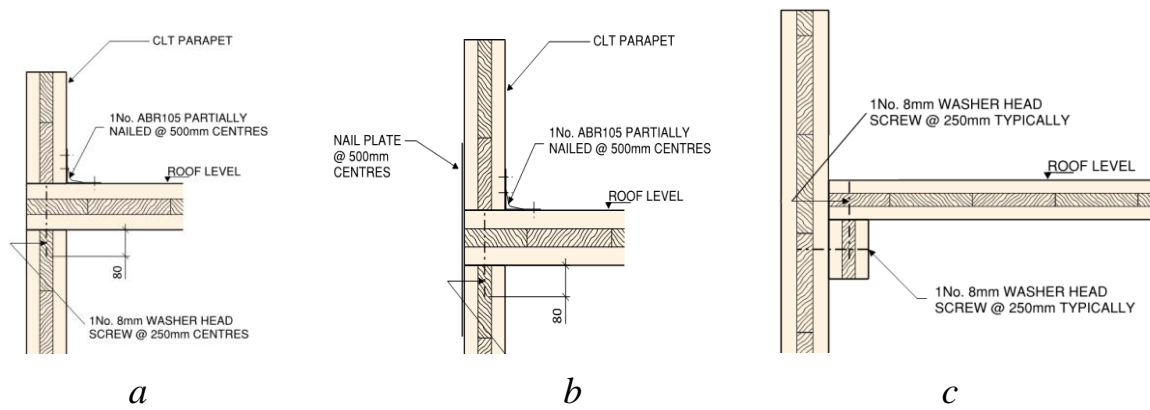


Fig. 15 Roof parapet connection options.

3.6 Special connections

There are some cases where a special connection detail is required to solve a localised high concentration of loads. Some typical examples of where special connections may be required are given below:

- High concentration of compression loads (e.g. reactions from stability walls or columns) can exceed the bearing capacity of the CLT. This is particularly likely if the wall or column is bearing on top of a CLT floor slab. There are three possible solutions: i) increase the wall thickness (or column section size), ii) locally reinforce the CLT floor panel with fully threaded screws (there are ETA's from screw manufacturers with methods to calculate buckling loads on self-tapping screws within timber) or iii) add a steel plate in the interface to spread the load over a larger area.
- A recent example encountered by the authors is a situation that required especial connections on cantilever stair half landings with steel angles (top and bottom) to form a moment connection (Fig 16).
- A common example of where non-standard connections are required is the fixing of localised steel elements such as lintel beams as shown in figure 17. This example shows how the bearing detail/connection can be pre-cut in the factory to help installation on site and minimise the number of connectors required.



Fig. 16 Special moment connection for a cantilever stair half landing slab.



Fig. 17 Special detail to support end bearing of a steel lintel beam.

4. Procurement of Connection Design – the challenges

It is typical UK practice for the detailed CLT connection design to be carried out as part of the CLT supplier/specialist contractor. This creates a problem for the CLT procurement process as discussed below.

In a typical CLT building the cost (supply only) of connections accounts for approximately 2-5% of the total CLT package cost (supply & erect cost). Whilst this cost may not appear as particularly significant, the influence of the structural design (i.e. type of connection selected) and the installation (i.e. time required) of connections is of major significance. The first action when designing the CLT connections is selection of the manufacturer of the screws and brackets. However, this creates a challenge for the engineer due to:

1. Different manufacturers = different connector types
2. Different manufacturers = different load capacities

The technical data for the connectors is typically contained in the manufacturers ETA document. However, there is considerable variability across different manufacturers in the availability and consistency of the technical data required by the engineer for the connection design – thereby creating another challenge in the design process.

In addition to this the procurement process of the design of CLT connections creates challenges for the engineer in similar manner to the CLT procurement process outlined previously in this paper. This is illustrated in the flow diagram below but can be described as follows:

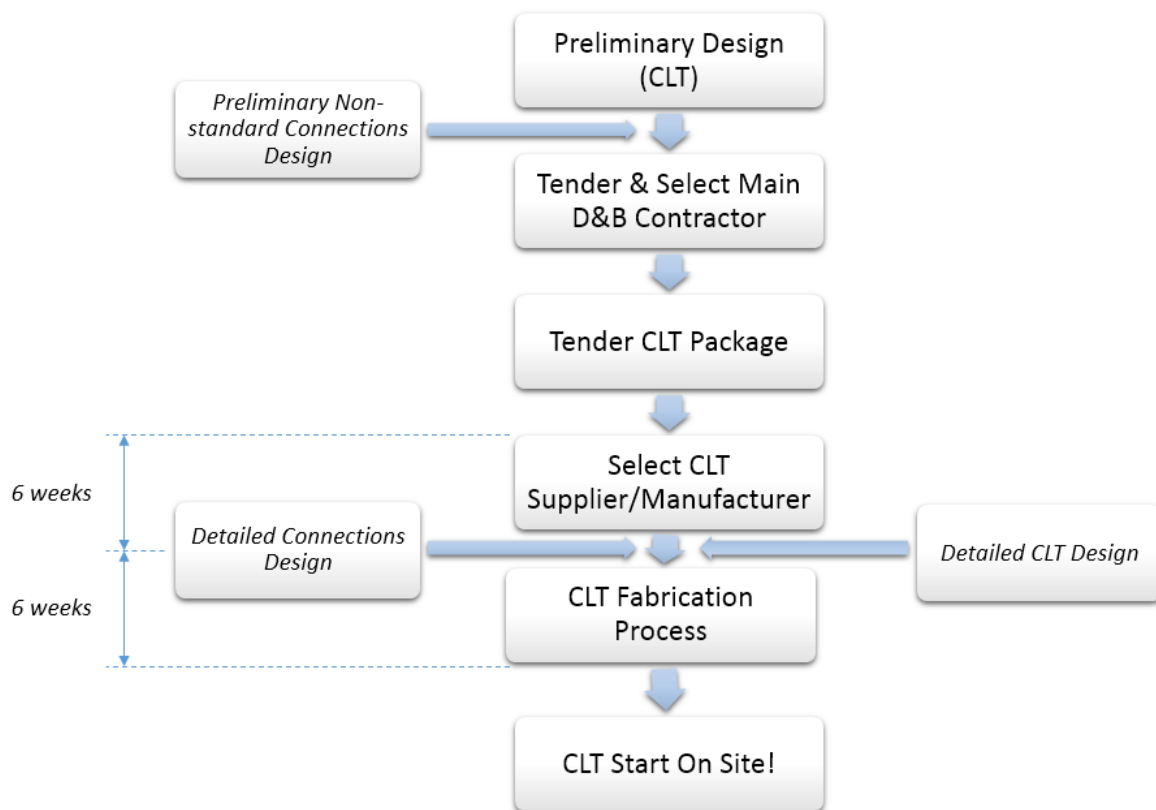


Fig. 18 Flow diagram illustrating the procurement process of a CLT building + connections.

The process of procuring connection design (Fig. 18) is in itself relatively logical. However, the main challenge to the engineer arises due to the typically fast track nature of modern construction programmes in the UK. Reference to the flow diagram shows that detailed connection design cannot commence until selection of the CLT supplier has been confirmed (and thereby the preferred connection manufacturer). Unfortunately (with fast track programmes) this tends to mark the point of commencement of the CLT fabrication process – typically 12-14 weeks in the UK. The result is that the engineer is put under immense pressure to deliver detailed connection design and detailed design of the CLT structure – all within a timeframe

which can be as little as 6 weeks (i.e. before commencement of CLT factory production/processing).

5. Conclusion, future challenges and acknowledgements

The design process of a CLT building is fundamentally influenced by the procurement process, and in particular by the choice of CLT manufacturer and connector supplier. An early appointment of the CLT supplier can speed up the design phase and avoid inefficiencies of the design process and problems when changing from one supplier to another in the middle or end of the process.

There is a lack of standardised design guidance in Europe. Technical design data currently has to be obtained from a combination of sources such as: manufacturer's European Technical Approval documents, expert reports and some design guides from timber associations such as the Canadian CLT Handbook [4]. That lack of consistency and formal agreement in how to design with CLT makes the designer go back to first principles and refer to some clauses from the Eurocode 5 [5] and thereby not utilising the full benefits of CLT as a system. This last point is particularly important as material efficiency of CLT buildings becomes increasingly important when comparing costs of CLT buildings with steel or concrete frames.

Some of the future challenges the CLT industry will need to address are as follows:

- Streamlining of the procurement and design process to avoid having to redesign buildings caused by a change in the manufacturers. Alternatively a list of standard board types which all manufacturers can make, i.e. overall thickness of the panel and thickness and orientation of each layer, should solve the need for any re-design.
- Affordable and easy to use structural analysis software for whole CLT structures based on multi-layer orthotropic panel elements. The current analysis software available either do not include those elements or are too expensive for a design office to purchase. There are free design software from institutions and some manufacturers. However they only cover the design of simple elements.
- Production of consistent and formal design guidance for CLT elements and connection details in CLT. One of the key areas where the lack of guidance is relevant is for vibration limit criteria for floor slabs and tie load requirements to avoid the disproportionate collapse (there are guidelines for tie loads for other construction materials but not for CLT). This might take the form of a European version of the Canadian & American 'CLT Handbook' produced by FP Innovations.
- Production of design guidance for CLT in seismic locations. It will not impact directly on the UK but it is relevant to many European countries.

- Address the timber engineering knowledge & skills shortage in the UK by introducing timber engineering as a core subject within university engineering courses.
- High rise CLT buildings: there have been several studies investigating the use of CLT in Supertall buildings. These identify one of the main issues to solve is the connections where the high stress concentrations lead to significant vertical movements. The design of connections is therefore one of the keys to unlock the opportunities for building taller in CLT.

The authors would like to acknowledge the contribution from Eurotec, Rothoblaas and Simpson Strong-Tie in sharing their connector images with us.

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