Title	Mass timber - the emergence of a modern construction material
Author(s)	Harte, Annette M.
Publication Date	2017-08-31
Publication Information	Harte, Annette M. (2017). Mass timber – the emergence of a modern construction material. Journal of Structural Integrity and Maintenance, 2(3), 121-132. doi:10.1080/24705314.2017.1354156
Publisher	Taylor & Francis
Link to publisher's version	https://dx.doi.org/10.1080/24705314.2017.1354156
Item record	http://hdl.handle.net/10379/16897
DOI	http://dx.doi.org/10.1080/24705314.2017.1354156

Mass timber - the emergence of a modern construction material

Annette M. Harte

College of Engineering and Informatics, National University of Ireland Galway,

Galway, Ireland

Ryan Institute for Marine, Environmental and Energy Research, National University of Ireland, Galway, Ireland

Annette.harte@nuigalway,ie

Mass timber - the emergence of a modern construction material

In the move towards sustainable construction, timber and wood-based products are becoming increasingly important structural materials. The introduction of mass timber products with excellent load carrying characteristics allows timber to be used in larger, more complex structures. Cross-laminated timber panel products have developed to the stage where they can be considered as economic and more sustainable alternatives to traditional materials. In this paper, the characteristics and design of CLT structures are described. Recent developments in mid- and high-rise CLT construction are reviewed and future opportunities identified. Current and future research needs are highlighted.

Keywords: mass timber; cross laminated timber; tall timber buildings

Introduction

Mass timber is a term used to describe a family of engineered wood products of large section size that offers the construction industry a viable alternative to steel and concrete. The term is generally applied to thick panel products but can also include large section glued- or block-laminated linear elements. There has been a significant level of interest in these products and building systems due to their technical capabilities, cost-competitiveness and environmental properties.

The product that has received most attention in recent years is cross-laminated timber (CLT), sometimes referred to as X-lam (Brandner et al., 2016). CLT is a prefabricated multi-layer engineered panel wood product, manufactured from at least three layers of parallel boards by gluing their surfaces together with an adhesive under pressure (Figure 1). Alternate layers of boards are placed cross-wise to each other, which gives the product a high level of in-plane stability. The large thickness gives CLT panels their exceptional strength and stiffness.

Since its introduction in the 1990s, CLT has been the subject of intensive research, which has enabled the development of product standards (CEN, 2015) and design guidelines (Gagnon & Pirvi, 2011; Karacabeyli, & Douglas, 2013). According to the UNECE/FAO Forest Products Annual Market Review 2014-2015 (UNECE/FAO, 2015), about 90% of CLT production worldwide is located in Europe, with a total production volume of 560,000 m^3 in 2014. The global production for 2015 is estimated at 650,000 – 700,000 m^3. Plants have recently opened or are planned in Canada, the US, Japan, China and New Zealand (Schickhofer et al., 2016).

Many buildings have been constructed using this technology across a range of building types mostly as low-rise construction. In the UK alone, over 100 educational buildings in CLT were constructed between 2003 and 2011 (Crawford et al., 2013). The use of CLT in mid-rise and high-rise buildings has received international media attention. To date, over 50 buildings between 5 and 14 stories tall have been completed (woodskyscrapers.com, 2017) and an 18-storey student residence is currently under construction in Canada with taller buildings planned.

In this paper, CLT as a construction material and system is examined, design approaches and some case study buildings are presented. In addition, the future for tall timber buildings, and current and future research needs are discussed.

Characteristics and design of CLT structures

Panel Manufacture

CLT panels are commonly manufactured to lengths, widths and thicknesses of up to 18 m, 5 m and 0.5 m, respectively. The number of layers forming a CLT panel is usually 3, 5 or 7. The European product standard for CLT, EN 16351 (CEN, 2015), permits layer thicknesses between 6 mm and 45mm; however, the standard layer thicknesses are 20, 30 and 40 mm. The recommended minimum board width is 4 times the thickness in order reduce rolling shear failures. For the manufacture of the panels, structural grade timber is dried to about 12% and planed to the required thickness. Defects are cut out and boards are finger-jointed to produce the required lengths. Boards are laid side by side and may or may not be adhesively bonded along their narrow edges. Successive layers are added and the stack is face-bonded under pressure. Depending on the finish required further surface treatment may be required. Openings for doors, windows and services are made using CNC machinery to tight dimensional tolerances. The panels are stored in batches in accordance with the construction sequence and transported to site for erection as required. This sequence is illustrated in Figure 2.

Characteristics of CLT

CLT provides opportunities to use timber products in a wider range of applications than was possible heretofore. Increased use of timber in building construction can contribute positively to sustainable building practices.

Timber is considered a natural, renewable resource, and extraction and manufacturing of timber products requires a very low amount of energy relative to more conventional structural materials used in construction. Prefabricated CLT building systems are easily erected in a low-dust, low-noise assembly with minimal site waste. Due to their low weight, there is reduced labour and craneage on site and rapid erection times. Ease of disassembly allows for reuse of the material and a more resource-efficient product life cycle. An important consideration is the fact that the timber building elements sequester carbon over their lifespan. Dry wood is about 50% carbon by weight and so mass timber buildings store considerable amounts of carbon. During the lifespan of the building, several forest rotations can take place with further carbon sequestration in the forest. Additional benefits accrue due the substitution effect, which is the avoidance of emissions associated with replacing more energy demanding materials with wood products (Sathre & O’Connor, 2010). Several studies have been carried out to quantify the environmental benefit of construction in timber using life cycle analysis procedures (Robertson et al., 2012, Durlinger et al., 2014, Dodoo et al., 2014, Dolan & Harte, 2014). Robertson et al. (2012) undertook a comparative cradle-to-construction site gate life cycle assessment of a five-storey concrete-framed office building and also a laminated timber design using CLT and glulam. Based on an analysis of the structural support system and the building enclosure, they found that the timber design had a lower environmental impact in 10 of 11 assessment categories. Durlinger et al. (2014) investigated the environmental performance of the 10-storey Forté apartment building in Melbourne. They found that the Forté building, which was constructed from CLT, has a 22% lower global warming potential than an equivalent building constructed using reinforced concrete as the main structural material. Dolan & Harte (2014) showed that, by switching from reinforced concrete to timber structural elements in a visitor centre building, a 74% reduction in the embodied carbon of those elements could be achieved. Dodoo et al. (2014) investigated three timber-based building systems for a 4-storey passive apartment building and found that the primary energy use for the CLT building was lower by 7% and 5% than the beam-and-column and modular volume element buildings, respectively. From an energy efficiency perspective, the use of CLT panels as part of the external building envelope makes it easier to achieve passive or net zero energy building standards as timber has a low coefficient of thermal conductivity and good air-tightness is achieved.

In addition to the sustainability benefits, one of the primary benefits of CLT construction is the use of offsite prefabrication allowing for high-quality certified production, independent of the weather. As holes and notches in panels can be pre-cut prior to arrival to site and assembling methods are straightforward, construction and project delivery times are improved and costs are reduced.

Cross-lamination gives CLT excellent in-plane and out-of-plane strength, rigidity, and stability characteristics (Brandner, 2016). The degree of anisotropy in properties and the influence of natural variations, such as knots, are reduced in comparison with construction timber, allowing for higher characteristic properties to be used in design. Due to the fact that timber is a low density material, overall building weight is reduced compared to other construction material, resulting in savings in foundation works. However, for tall CLT buildings, the light weight may be a disadvantage when considering overturning effects due, for example, to wind loads, and additional measures such as tie-down rods may be required.

The use of CLT panels gives increased flexibility in architectural design as openings can be regular or irregular and placed at random. Where the panels are left exposed, building aesthetics are greatly enhanced as the exposed timber provides a warm sensation. Exposed timber in schools and healthcare buildings has been shown to have psychological benefits with heart rates and stress levels reduced, which has been found to result in higher levels of concentration in schoolchildren and faster recovery rates for patients (Fell, 2010; Sakarugawa et al., 2005; Elias, 1989).

CLT elements and building systems

CLT panels are suitable for use as floors, walls and roofs and can be used in combination with other engineered wood products, concrete, steel and masonry. CLT panels can be vertically oriented as load-bearing walls and shear walls, or horizontally as load-bearing floors or roofs. CLT panels have been widely used in low-rise construction but are increasingly used for mid- and high-rise residential construction. Walls typically use three- to five-layer panels, whereas for floors panels with five or more layers are used. For longer spans and unduly heavy loads timber-concrete composite floors provide an economic solution.

For low-rise buildings, platform construction is widely used. On each level, CLT walls are erected in a cellular arrangement and the floor is placed on top. The floor then provides a platform from which to construct the next level (Figure 3). With increasing building height, the compressive force, in the perpendicular to grain direction, from the walls above acting on the floor below increases. To prevent excessive deflections, the force can be transferred to the wall or column below by means of self-tapping screws or other steel connectors. An alternative approach is to use balloon construction methods in which the walls are continuous from floor to floor and the floors are supported by steel brackets connected to the walls. In this way, the compressive loading perpendicular to grain issue is avoided but scaffolding may be required to support the floor during construction. For mid- and high-rise buildings, different arrangements of CLT elements in conjunction with glulam beams and columns have been used with the structural core constructed either from concrete or CLT. Some of these solutions are described below.

Structural design of CLT

Due to the lack of experience with CLT when Eurocode 5 (CEN, 2004) was developed, no specific design rules for CLT were included. In the intervening years, design rules have been developed and are included as part of product-specific technical approvals and also in the National Annexes to Eurocode 5 in Austria and Germany. In Canada and the United States, CLT Handbooks (Gagnon & Pirvi, 2011; Karacabeyli, & Douglas, 2013) containing detailed design rules have been published. The CEN standardisation committee, CEN/TC 250/SC5, has established a working group to draft new design rules for inclusion in the next revisions to Eurocode 5. Recommendations for the design of CLT elements have been well documented in publications emanating from the European COST Actions (Harris et al., 2013; Thiel & Brandner, 2015).

For elements loaded out of plane, such as floors and roofs, the serviceability limit state deflection and vibration limits generally govern the design. An important consideration that arises from the cross-lamination of members is the shear flexibility of the cross layers. Because of this, deflection calculations based of one of the following methods is used: the Gamma method, the shear analogy method and the Timoshenko shear flexible beam method. These methods generally give comparable results where the span-thickness ratio exceeds 15. In the calculation of the stresses, for simplicity only those layers oriented perpendicular to the axis of bending are assumed to contribute to load resistance. This is illustrated in Figure 4 for the case of bending stresses.

For elements loaded in-plane, the two main loading scenarios are compression and shear. For CLT walls carrying vertical loading, compressive stress and buckling checks are performed. For buckling, verification by either the equivalent beam method or using 2nd order theory is used. For CLT shear walls, a number of different failure mechanisms are possible depending on whether the narrow edges of the layers are bonded or unbonded (Brandner et al., 2015). For CLT panels with the narrow edge bonded, failure is generally in gross-shear, where shearing of all of the layers takes place. Where there is no edge bonding, failure can occur through net-shear failure by exceeding the shear resistance of the layers oriented in the weak direction or by torsion failure of the glueline between the layers. Further information on these and other design checks is detailed in (Harris et al., 2013).

Connection between the CLT elements is achieved via simple steel connectors and self-tapping screws (Figure 5). The design of these connections can be carried out in accordance with current Eurocode 5 procedures.

Fire performance of CLT

Over the past couple of decades, research and testing has been performed to characterise the fire performance of timber structures so that safe fire design can be conducted (Gerard et al., 2013; Frangi et al., 2008; Frangi et al., 2009; Brandon et al., 2015). It is well known that, when ignited, timber burns at a predictable rate with the formation of a charring layer. This charring layer forms a thermal barrier between the surface and the internal timber. During a fire incident, the cross-section of the timber element reduces at a predictable rate. Due to the large section size of mass timber members, they have an inherent fire resistance. Many studies have been undertaken to establish the charring rates for mass timber elements. In Figure 6, a CLT panel after a 1-hour fire test is shown. The exposed face of the panel shows the char formation while the unexposed face shows no evidence of deterioration. In tests on CLT panels manufactured with temperature-sensitive adhesives (Frangi et al., 2009), the charred layer delaminated during the tests resulting in increased charring rates, which can be characterised using a bi-linear charring model. For panels manufactured with less temperature-sensitive adhesives, the charred layers remained in place and continued to protect the layers underneath against increasing temperatures. This behaviour is the same as for solid panels and provides a constant charring rate throughout.

In order to achieve a specific level of fire resistance, different measures are used. The CLT panels can be sized to ensure that the required resistance is met. The reduced section after the end of the fire duration must still have adequate capacity to carry the loads. Another approach is to encapsulate the panels with fire-rated gypsum boards. The combined resistance of the panels and gypsum boards provide the necessary fire rating. The next level of fire protection is to provide a sprinkler system.

Tests on several full-scale buildings have been conducted to investigate the influence of combustible surfaces on fire growth and fire spread inside and outside the room containing the fire (Frangi & Fontana, 2005, Frangi et al., 2008). As part of the SOFIE project (Frangi et al., 2008), tests were carried out in Japan on a full-scale 3-storey CLT building under natural fire conditions to check the global performance and to find possible weaknesses in the timber structure. The walls and floors of the building comprised 85 mm thick and 142 mm thick CLT panels, respectively. They were encapsulated in either one or two layers of non-combustible gypsum board. The windows in the fire room were left open during the test. After the 1-hour fire test, all of the gypsum boards had completely fallen off and the measured charring depth varied between 5 mm and 10 mm. The tests confirmed that, with pure structural measures, it is possible to limit the fire spread to one room even for timber structures. There was no fire spread to adjacent rooms and in the room above the fire room, no elevated temperature or smoke were detected.

As new timber technologies are developed and, in particular, connections that transfer loads between elements, it is important to consider the fire performance of these assemblies. As most connectors are manufactured from steel, it is essential as part of the fire design to account for the potential of the connectors to conduct heat into the core of the panels. In addition to connection behaviour in fire, understanding penetration behaviour is critical to demonstrate that compartmentation is achieved.

In the current regulatory environment, testing is generally required to prove compliance for mid- and high-rise buildings. For recently constructed tall CLT buildings, the fire design has often been conservative. Sprinkler systems have been included even when compliance was deemed to have been achieved with encapsulation on the basis of the tests. Testing is also an important part of the ongoing fire engineering research that will underpin the development of standards.

CLT buildings – current practise and future trends

The last 20 years has seen the completion of a large number of CLT buildings, mainly in Europe (Mayo, 2015). The earlier projects were mainly single family dwellings but this quickly expanded to the multi-family residential, educational and commercial sectors. Due to the expertise developed with earlier projects and a significant level of research, the last 10 years have seen a significant move to using this technology in the mid- to high-rise construction sector. In Table 1, a list of all buildings of 5-storey and above completed in the period 2005-2016 is given (woodskyscrapers.com, 2017). Over that period, increases have taken place in the number of projects, the height of the buildings, the use type and geographic spread. The 10-storey Forté apartment building in Melbourne was the tallest CLT building in the world when completed in 2012. This was overtaken in 2015 by the 14-storey TREET building in Norway, but this record will be broken in 2017 when the 18-storey Brock Commons student residence is completed in Canada. A number of proposals for even taller buildings have been put forward and studies have shown that very tall buildings utilising CLT are feasible.

Many of the early adopters of CLT as a primary construction material were in regions or municipalities where ‘Timber First’ or sustainable policies were in place. The London borough of Hackney is the first local authority in England to promote timber construction. Since it introduced a ‘Timber First’ policy in 2012, more than 18 multi-storey timber buildings have been built in the region. One of these buildings, the Stadthaus in Murray Grove, was the tallest timber building in the world when it was completed in in 2009 and it has received considerable international attention since that time. Vancouver aims to be the greenest city in the world by 2020 and is the site for what will be the highest CLT building when it is completed in 2017.

Three case study buildings are presented and future trends in high-rise construction are discussed.

Case study 1: Limnologen apartment complex, Växjö, Sweden *(Serrano, 2009)*

In the Välle Broar region in the municipality of Växjö in Sweden, a town planning strategy was developed in 2002 to increase the use of wood in construction. As part of this strategy, it stated that in the Välle Broar region, all construction must be based on the use of timber or wood based products. As a result of an architecture competition, the Limnologen complex was born. It consists of four eight-storey apartment buildings, with seven timber storeys on a concrete foundation and concrete first floor (Figure 7).

The primary loadbearing structure comprises CLT panels, which is used in both the floors and walls. All exterior walls and some of the interior walls carry the vertical loads. The horizontal loads are transferred by the floors, acting as stiff plates, to the top of the walls. In some parts of the buildings, glulam columns and beams have supplemented the load bearing system in order to reduce the deformations. The load-bearing floor elements comprise 3-layer CLT panels acting compositely with tee-shaped glulam beams. Tension rods, anchored to the concrete at first floor level are required to carry the overturning forces due to wind loading. The tension rods were re-tightened after some time due to relaxation in the steel, creep deformations in the timber and due to possible drying of the timber.

In order to minimise the risk of flanking transmission and impact sound transmission, the walls are not continuous across storeys, and a polyurethane sealant is used between the walls and the flange of the floor elements. Separation of the floor elements from the ceilings directly below forms part of the acoustic design (Figure 8).

As these buildings were unique in Sweden, they were designated as research and educational buildings. Linneaus University and the SP Technical Research Institute have access to Välle Broar projects and both continue to monitor the buildings. Monitoring of vertical shortening, sway, sound transmission, and structural vibrations are ongoing.

Case study 2: Mayfield school, Kent UK

This award-winning project involved the expansion of an existing 1,000 pupil secondary school to accommodate an additional 800 pupils and 80 teachers, requiring an 8,000 m^2 expansion. The development had an 18-month timeframe in what was an active school site and had to achieve a BREEAM "excellent" target environmental performance rating (Ramboll, 2016).

Because of these constraints, the structural solution chosen was CLT together with glulam beams and columns. Steel beams were used for particularly long spans in a small number of cases. The use of off-site manufacturing reduced the time on site and the superstructure was completed in 12 weeks. Figure 9 shows the buildings under construction (Hartmann, 2015). The lightweight timber significantly reduced the substructure works compared to a traditional concrete structure. Another key factor in achieving a shortened construction time was the use of an integrated building information modelling (BIM) approach. Where possible, the timber was left exposed, due to its aesthetic appeal, to provide a warm interior, and to take advantage of beneficial effect on learning provided by timber interiors.

Case study 3: Brock Commons student residence, Vancouver, Canada *(Acton Ostry, 2016)*

Construction of the Brock Commons student residence at the University of British Columbia (UBC) in Vancouver is expected to be completed in Spring 2017, six months ahead of schedule. This 18-storey building will provide accommodation for over 400 students. The superstructure of the building comprises a reinforced concrete ground floor and two reinforced concrete cores while the remaining 17 floors comprise CLT panels and glulam columns (Figure 10). The 17 timber floors were erected in 2016 over a period of 9 weeks using a single crane. On completion, the 53 m tall Brock Commons will be the tallest timber structure in the world and will have a floor area in excess of 14,500 m^2.

UBC aims to achieve LEED Gold certification for the building. In addition to its primary function as a student residence, the building will serve as a living laboratory for students and researchers, who will be able to study and monitor its operations.

The floor structure comprises 5-layer two-way spanning CLT panels supported on glulam columns on a 2.85 m x 4.0 m grid. The vertical loads are carried by the CLT floor structure and glulam column while lateral stability is provided by the concrete cores and CLT diaphragms at each level. To prevent vertical load transfer through the CLT panels, steel connectors are used to transfer the columns loads directly to the column below.

The construction cost for this innovative building is estimated to be about 8% higher than comparable reinforced concrete building. This cost difference is expected to reduce as more CLT suppliers enter the marketplace and designers and builders become more familiar with mass timber construction methods. Due to the uniqueness of this project, a conservative approach to the fire safety design was taken. The timber elements will be encapsulated in gypsum panels to give a 2-hour fire separation between compartments and an automatic sprinkler system with a back-up water supply will be installed.

CLT construction in Ireland

Compared with the UK, where over 600 CLT buildings have been constructed, this form of construction is relatively new to Ireland and until recently has been limited to single family dwellings. Two recently commercial completed buildings in Dublin, the Ballyogan Environmental Management Centre and the Samuel Beckett Civic Campus have used CLT for walls, floors and roofs. In Figure 11, the Samuel Beckett building and a view of its interior are shown. There are plans to construct a 7-storey hotel using CLT. Given the success of this building system globally, it is expected that CLT construction will increase as with the construction industry grows over the coming years.

Tall timber buildings – the future

As can be seen from Table 1, timber buildings made from mass timber have been getting progressively taller. The tallest completed building is the 14-storey Treet building in Norway which is 49 m tall. When completed, the 18-storey Brock Commons student residence in Canada will be 53 m tall. The drive to develop tall buildings arises due to the demands for housing to cater for increasing global population and increased urbanisation. Tall buildings present unique challenges for structural designers. In order to investigate the technical and economic feasibility of using mass timber in tall buildings, to quantify the environmental benefit and to identify research needs, a number of international studies have been undertaken, including the *Case for Tall Wood Buildings* project, and the *Timber Tower Research* project. In these projects, different structural solutions for tall buildings are proposed, which use timber as the primary structural material but also incorporate steel and concrete elements.

In 2012, Vancouver-based Michael Green Architecture unveiled a conceptual design for 30-storey timber residential buildings in a report entitled *The Case for Tall Wood Buildings* (Green, 2012). The structural system, known as the FFTT system, is based on a 'strong column-weak beam' balloon frame approach. The system combines mass timber panels as the vertical structure, lateral shear walls and floors. The 'weak beam' component refers to steel beams, which are bolted to the timber panels, to provide ductility in the system under wind and seismic loading.

The use of the FFTT system for four case study buildings was investigated: Option 1 - 12-storey building with core only, Option 2 - 20-storey building with core and interior shear walls, Option 3 - 20-storey building with core and perimeter moment frames and Option 4 - 30-storey building with core and perimeter moment frames and interior walls. These options are illustrated in Figures 12 and 13. The gravity load-resisting system comprises CLT or CLT/concrete composite panels, designed to span one way over interior steel beams, which also act as link beams. The perimeter structure consists of glulam post-and-beam frames for Options 1 and 2, and moment-frames of solid wood panels and steel link beams for Options 3 and 4. The lateral load resistance is provided by three lateral load resisting systems: the core, the perimeter moment frames, which would be integrated into the building facades, and interior partition walls used individually or in combination. Stiffness governs the design in most cases, with wind loading most critical for higher buildings even in higher seismic zones, due to the relatively low building mass.

A cost analysis was conducted for both 12-storey and 20-storey FFTT options, considering both the charring and the encapsulation approach to fire protection, and costs were compared to equivalent reinforced concrete frame structures. For both building heights, the costs for the FFTT structures with the charring option were the same as the concrete structures but were 2% higher for the encapsulated approach. There is an expectation that as the design and development of FFTT building advances, there will be significant reductions in the construction costs.

Further research and development is required to validate the FFTT system including: advanced analysis of the lateral load resisting systems and connection options; testing of frame behaviour and typical connections; fire testing and modelling.

The *Timber Tower Research* project (Skidmore et al., 2013) was undertaken by Skidmore, Owning and Merrill (SOM), designers of many tall buildings including the Burj Khalifa in Dubai. The aim of the study was to develop a structural system for tall buildings using timber as the main structural elements and which minimises the carbon footprint of the building. The feasibility of a new structural mass timber system that can be designed to be competitive with reinforced concrete construction in buildings from 10 to 30 stories in height, while reducing the embodied carbon footprint by approximately 60%-75%, was demonstrated. The design solution proposed includes a novel concrete-jointed timber frame. Mass timber is used for the primary members (floors, shear walls and columns) and these are connected with steel reinforcing through concrete joints. The floor system is illustrated in Figures 14 and 15.

The proposed structural system was applied to a prototype building based on an existing concrete building designed by SOM. The Dewitt-Chestnut apartment building, built in Chicago in 1966, is a 395' tall 42-storey concrete structure. This building was selected as the data was readily available and, as it made very efficient use of materials, it provides a lower-bound for comparison. The timber design, utilising the concrete jointed timber frame is illustrated in Figure 16. The gravity load-resisting system comprises CLT floor panels that span between the timber shear walls at the centre of the building and the reinforced concrete spandrel beams and timber columns at the perimeter. The concrete beams stiffen the floor thereby enhancing the deflection and vibration characteristics, leading to a more efficient design. The beams transmit the floor loads via the columns and walls to the lower floor and eventually to the foundations. The lateral load-resisting system comprises CLT shear walls located near the core, designed to resist the wind loading in both directions and overall building torsion. Additional shear walls across the narrow building dimension are necessary to resist uplift due to wind loading on the wide faces of the building. The foundations and the lower two floors of the building are concrete. Overall, the building is 70% timber and 30% concrete.

A limited cradle-to-gate life cycle analysis was carried out to assess the relative environmental performances of the prototype and benchmark buildings. This included only the embodied carbon associated with the materials used and the energy used in the construction. Two scenarios were considered for the benchmark building: 'standard materials' and 'sustainable materials'. The 'sustainable materials' option considers the use of cement replacement and air-drying of the wood. The carbon emissions associated with construction were taken as the same for all cases. The embodied carbon footprint of the prototype building was found to be 60% lower than that of the benchmark building for the 'sustainable materials' option and 75% lower when considering the 'standard materials' options.

CLT research

In order to support the certification and wider use of this building system a considerable amount of research is underway across the globe. Areas of research which have been identified by EU COST Actions, Code Committees and feasibility studies, such as those described above, include: technical properties, connection behaviour, vibration behaviour, fire, and sustainability. Two current COST actions, FP1402 and FP1404, bring together researchers on CLT in order to optimise the effectiveness of the individual efforts.

Use of locally-grown timber

Due to the increase in global demand for CLT, research is underway in many countries to determine the suitability of native timber for CLT manufacture. In Europe, CLT is mainly manufactured using grade C24 spruce. In a recently completed research project, the viability of using fast-grown Grade C16 Irish grown Sitka spruce to manufacture CLT panels was established (Sikora et al., 2015). The in-plane and out-of-plane bending performance of Irish CLT panels has been established and rolling shear characteristics have been determined. The influence of layer thickness on the bending characteristics has been identified as an important factor in design (Sikora at al., 2016). Flexural testing of a panel is shown in Figure 17 and typical rolling shear failure of the cross layer is seen in Figure 18. The flexural stiffness of the Irish panels compared well with commercial CLT panels manufactured from Central European spruce. The development of a CLT manufacturing plant in Ireland presents an opportunity to add significant value to the output from Irish forests and to increase employment in rural areas. In addition, the use of locally grown material will enhance the environmental sustainability of the construction industry.

Vibration characteristics of CLT floor systems

One of the significant advantages of CLT construction is the reduction in building weight. However, this can have a negative impact on the vibration behaviour. As the serviceability limit state usually governs design, the deflection and vibration characteristics of CLT floor systems require careful consideration to ensure an acceptable level of comfort for users. Eurocode 5 design provisions for vibrations are limited and further research is necessary to establish more detailed guidelines for design. The influence of the connection system configuration and the influence of structural and non-structural concrete toppings on the dynamic performance of CLT floors are currently under investigation (UíChúláin et al., 2016) with a view to optimising the serviceability design (Figure 19). Testing of different floor systems both in the laboratory and in-situ in buildings is being undertaken in parallel with numerical modelling to establish acceptable approaches and new design guidelines.

Conclusions

The use of CLT in construction is growing and is being used in increasingly demanding applications. This trend is being driven by the challenge of sustainable construction and is being enabled by research and development across the globe that is driving the technology forward. Tall timber buildings can achieve the same level of performance as steel and concrete. As the technology develops, standardised approaches to the structural and fire design of these buildings will evolve to support the wider use of CLT construction. In this paper, recent developments in CLT materials and construction methods have been reviewed, examples of exemplar CLT buildings have been presented and studies to extend the technology to deliver buildings over 40-storeys tall have been discussed.

References

1. Acton Ostry Architects Inc. (2016), *A tale of tall wood. Brock Commons student residence, University of British Columbia,* Vancouver, Canada.
2. Brandner, R., Dietsch, P., Droscher, J., Schulte-Wrede, M., Kreuzinger, H., Sieder, M., Schickhofer, G, Winder, S. (2015). Shear properties of cross laminated timber (CLT) under in-plane load: test configuration and experimental study. *Proceedings of 2nd INTER Meeting,* Sibenik, Croatia
3. Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., Thiel, A. (2016). Cross laminated timber (CLT): overview and development. *European Journal of Wood and Wood Products, 74(3),* 331-351.
4. Brandon, D., Maluk, C., Ansell, M.P., Harris, R., Walker, P., Bisby, L., Bregulla, J. (2015). Fire performance of metal-free timber connections. *Proceedings of the ICE - Construction Materials, 168(4),* 173-186.
5. CEN. (2004). *EN1995-1-1: Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings*, CEN European Committee for Standardisation, Brussels, Belgium.
6. CEN. (2015). *EN16351*: *Timber structures - cross laminated timber- Requirements*, CEN European Committee for Standardisation, Brussels, Belgium.
7. Crawford D., Hairstans R., Smith R.E. (2013). Feasibility of cross-laminated timber production from UK Sitka spruce. *Proceedings of European Conference on Cross Laminated Timber*, Graz, Austria. 37-52.

8. Dolan, D., Harte, A.M. (2014). A Comparison of the Embodied Energy and Embodied Carbon of a Timber Visitor Centre in Ireland with its Concrete Equivalent. *Proceedings of World Conference on Timber Engineering*, Quebec, Canada.
9. Dodoo, A., Gustavsson, L., Sathre, R. (2014). Lifecycle primary energy analysis of low-energy timber building systems for multi-storey residential buildings. *Energy and Buildings, 81*, 84-97.
10. Durlinger, B., Crossin, E., Wong., J. (2013). *Lifecycle assessment of a cross laminated timber building.* Project No. PRA282-1112. Forest and Forest Products Australia.
11. Elias, MJ. (1989). Schools as a source of stress to children: an analysis of causal and ameliorative influences. *J of School Psychology 27*, 393-407.
12. Fell, D. (2010), *Wood in the human environment : restorative properties of wood in the built indoor environment*, PhD thesis, University of British Columbia
13. Frangi, A., Fontana, M. (2005). Fire performance of timber structures under natural fire conditions, *Fire Safety Science 8*, 275-290.
14. Frangi, A., Fontana, M., Hugi, E., Jobstl, R. (2009). Experimental analysis of cross-laminated timber panels in fire. *Fire Safety Journal 44*, 1078-1087.
15. Frangi, A., Bochicchio, G., Ceccotti, A., Lauriola, M.P. (2008). Natural full-scale fire test on a 3 storey Xlam timber building. *Proceedings of 10th World Conference on Timber Engineering*, Miyazaki, Japan.
16. Gagnon, S., Pirvi, C. (eds). (2011) *CLT Handbook: cross-laminated timber, Canadian Edition*, FP Innovations, Quebec, CA.
17. Gerard R., Barber D., Wolski A. (2013) *Fire safety challenges of tall wood buildings*. Arup North America, San Francisco, CA, and Fire Protection Research Foundation, Quincy, MA, USA.

18. Green, M. (2012). *The Case For Tall Wood Buildings*. mgb Architecture + Design, Vancouver, Canada.
19. Harris, R., Ringhofer, A., Schickhofer, G. (2013). *Focus solid timber solutions - European conference on cross laminated timber (CLT),* University of Bath, Bath, UK.
20. Hartmann, K. (2015). Mayfield School. CLT + BIM = Added value. *Presentation to IITU Industry Seminar*, NUI Galway, Ireland.
21. Karacabeyli, E., Douglas, B. (2013) *CLT Handbook: cross-laminated timber, US Edition*, FP Innovations. Quebec. CA.
22. Mayo, J. (2015). *Solid wood: Case studies in mass timber architecture, technology and design*, Routledge, Abingdon, UK.
23. Ramboll. (2016). *Mayfield School*, //www.ramboll.com/projects/ruk/mayfield-school, Accessed:050716.
24. Robertson, A.B., Lam, F.C., Cole, R.J. (2012). A comparitive cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: laminated timber or reinforced concrete. *Buildings*, *2,* 245-270.
25. Sakarugawa, S., Miyazaki, Y., Kaneko, T., Makita, T. (2005). Influence of wood wall panels on physiological and psychological responses. *J of Wood Science, 51*, 136-140.
26. Sathre, R., O'Connor, J. (2010). Meta-analysis of the greenhouse gas displacement factors of wood product substitution. *Environmental Science & Policy, 13*:104:114.
27. Schickhofer, G., Brandner, R., Bauer, H. (2016). Introduction to CLT, product properties, strength classes. *Proceedings of Conference of COST Actions FP1402 and FP1404*, Stockholm, Sweden.

28. Serrano, E. (2009) *Documentation of the Limnologen project*, Report No 56, Vaxjo University, Sweden.

29. Sikora, K.S., McPolin, D.O., Harte, A.M. (2015), 'Shear strength and durability testing of adhesive bonds in cross-laminated timber, *J Adhesion*, 92(7-9), 758-777.

30. Sikora, K.S., McPolin, D.O., Harte, A.M. (2016), 'Effects of the thickness of cross-laminated timber (CLT) panels made from Irish Sitka Spruce on mechanical performance in bending and shear', *Construction and Building Materials*, 116, 141-150.

31. Skidmore, Owings, and Merrill, LLP. (2013). *Timber Tower Research Project*. https://www.som.com/sites/default/files/20130506_SOM-Timber-Tower-Final-Report_1.pdf. Accessed January 14, 2014.

32. Thiel, A., Brandner, R. (2015). ULS design of CLT elements - basics and some special topics. *Proceedings of Cross Laminated Timber - a competitive wood product for visionary and fire safe buildings: Joint Conference of COST Actions FP1402 and FP1404*, KTH, Stockholm, Sweden.

33. Uí Chúláin, C., Sikora, K, Harte, A. (2016), 'Influence of connection systems on the serviceability response of CLT timber flooring', Proceedings of World Conference on Timber Engineering (WCTE16), Vienna, Austria.

34. UNECE/FAO. (2015) *Forest Products Annual Market Review 2014-2015*. http://www.unece.org/forests/fpamr.html.

35. www.woodskyscrapers.com/. Accessed: 310117.

Table 1. Multi-storey CLT buildings completed 2005-2016.

Year	**Building Type- No. storeys (Country)**
2005	*R-5 (NO); R-5 (UK)*
2006	*R-6 (CH)*
2008	*R-7 (DE); R-8 (SE); R-10 (SE)*
2009	*R-8 (UK)*
2010	*O-6 (CA)*
2011	*R-6 (DE); R-8 (UK); R-8 (DE)*
2012	*R-5 (FI); E-5 (CA); R-6 (UK); O-8 (AT); R-10 (AU)*
2013	*R-5 (DE); R-6 (CA); O-6 (CH); O-6 (US); H-6 (IT); R-7 (FR); R-7 (AT); R-7 (IT); R-8 (NO); R-9 (IT)*
2014	*O-5 (AT); M-5 (TW); E-6 (CA); R-7 (UK); R-8 (ES); R-8 (FR); R-8 (NO); R-7 (UK); R-10 (UK*
2015	*R-5 (IT); R-5 (AU); O-5 (US); R-6 (UK); M-6 (UK); R-8 (FI); R-10 (UK); R-14 (NO)*
2016	*R-5 (FR); R-5 (FR); R-5 (FR); R-5 (UK); R-5 (BE) R-5 (FI);O-7 (US)*

Building types: R- residential, O – office, H – hotel, E- education, M – mixed use

List of figures

Figure 1 5-layer CLT floor panel.

Figure 2. Manufacture, transportation and erection of CLT panels [*Images: KLH*].

Figure 3. Platform construction [*Image: C UíChúláin*]

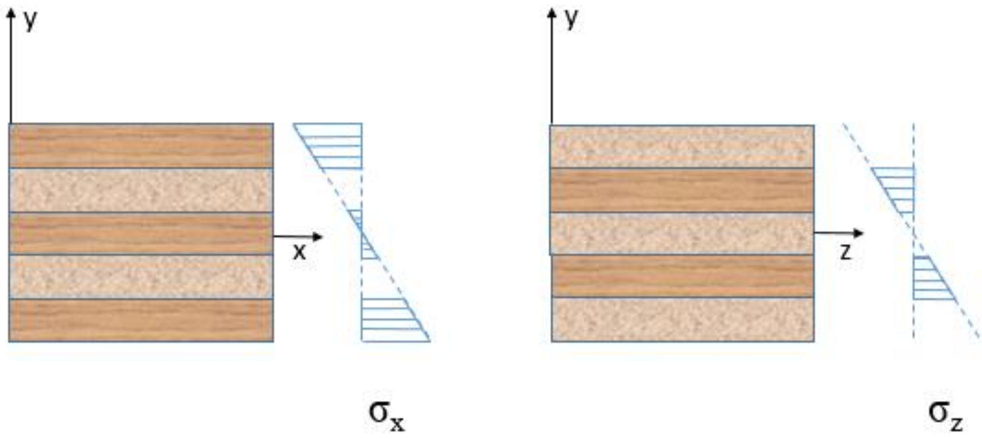
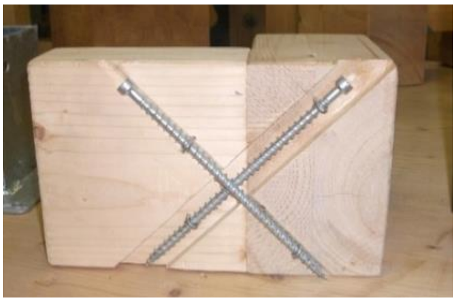


Figure 4. Stress distribution in CLT: σ_x major axis bending; σ_y minor axis bending.



(a)

(b) [*Image: C UíChúláin*]

Figure 5. Connectors for CLT: (a) self-tapping screws; (b) steel angle brackets

(a) (b)

Figure 6. CLT panel after 1-hour fire test (a) unexposed face (b) exposed face.

Figure 7. Limnologen apartment buildings, Sweden.

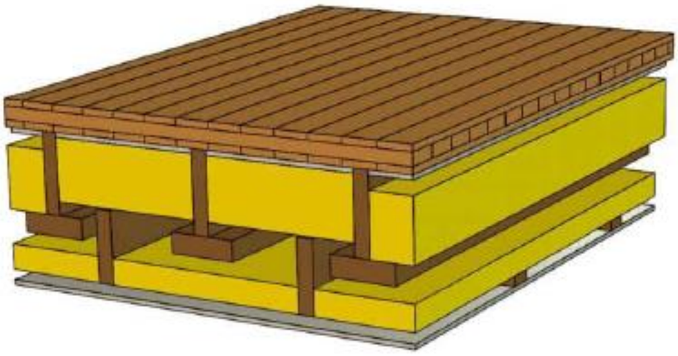


Figure 8. Limnologen floor-ceiling detail (Serrano, 2009).

Figure 9. Mayfield school – construction phase (Hartmann, 2015).

[*Image courtesy of Acton Ostry Architects Inc. Photographer: Michael Elkan*]

[*Image courtesy of naturally:wood.com. Photographer: KK Law*]

Figure 10. Brock Commons student residence (Acton Ostry, 2016).

Figure 11. Samuel Beckett Civic Campus [*Images: C Uí Chúláin*].

Figure 12. FFTT building frames: Options 1(12-storey) & 2 (20-storey) (Green, 2012).

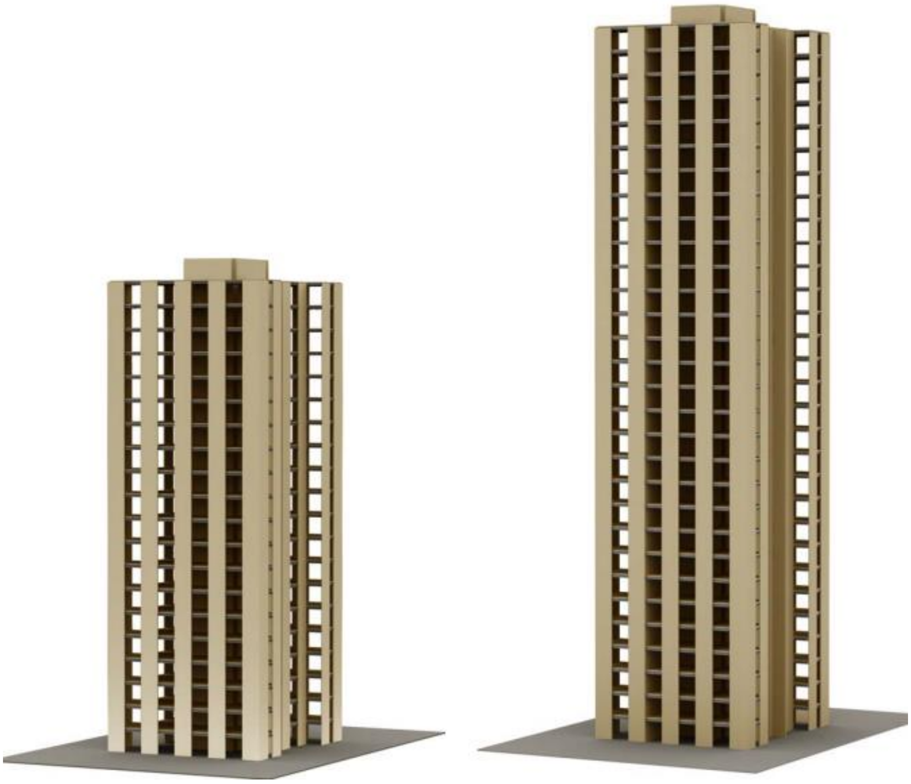


Figure 13. FFTT building frames: Options 3 (20-storey) & 4 (30-storey) (Green, 2012).

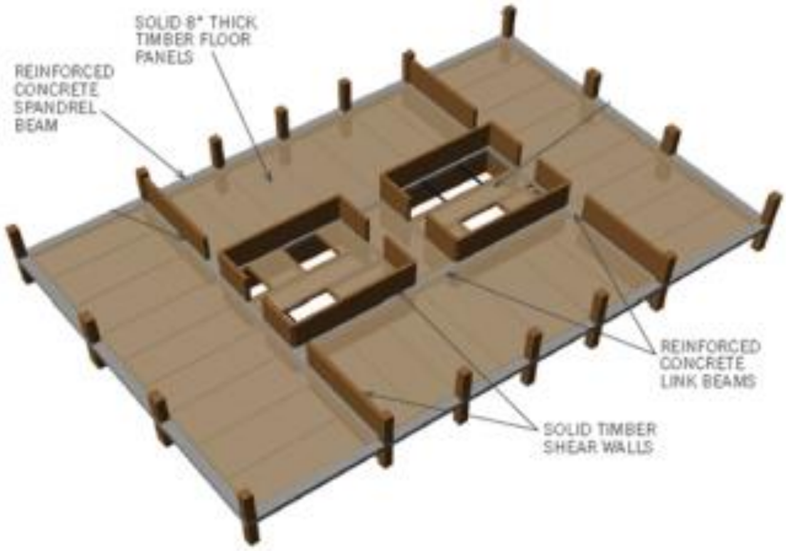


Figure 14. SOM concrete-jointed timber frame (Skidmore et al., 2013).

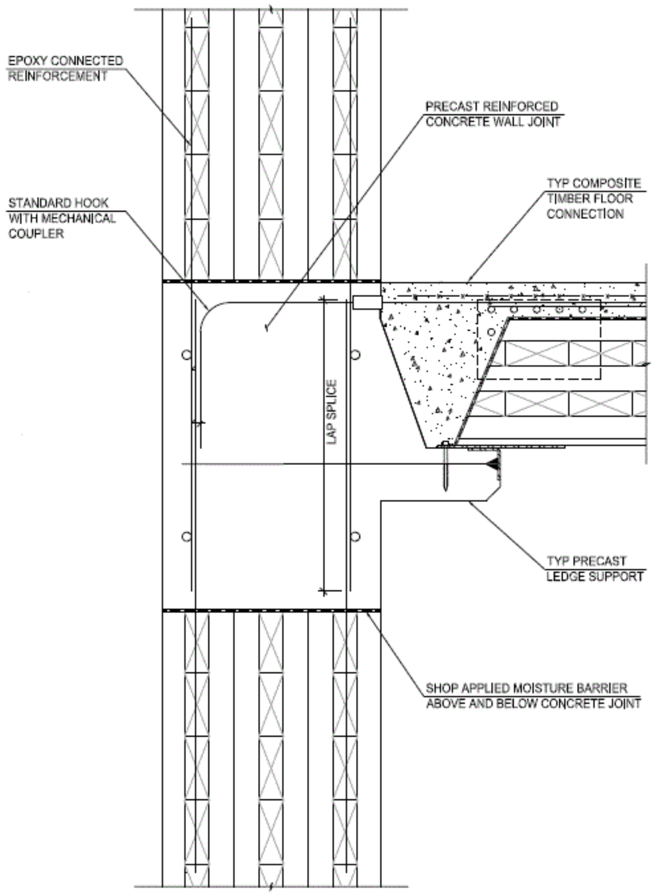


Figure 15. SOM concrete joint detail (Skidmore et al., 2013).

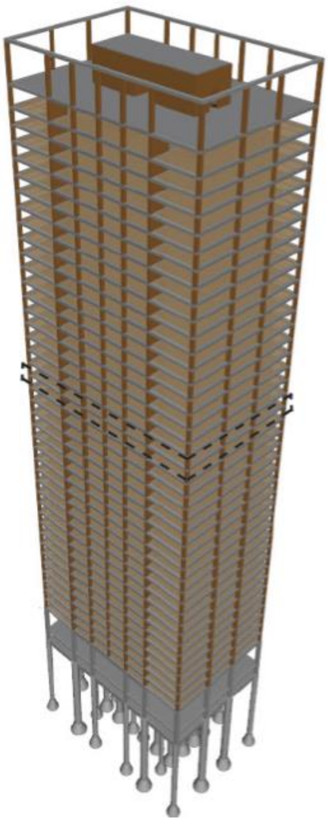


Figure 16. SOM 42-storey timber prototype (Skidmore et al., 2013).

Figure 17. Out-of-plane bending test on Irish CLT panel.

Figure 18. Rolling shear failure of Irish CLT panel.

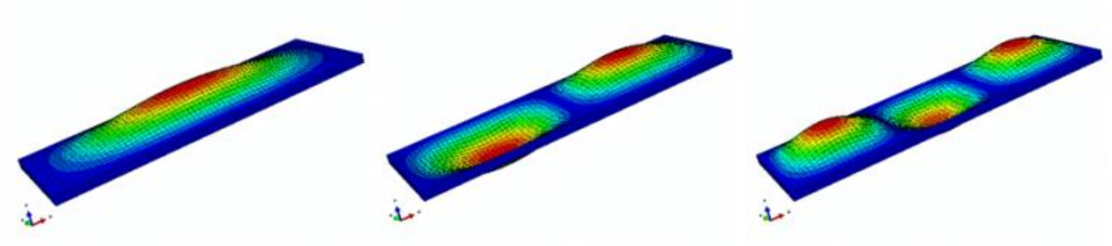


Figure 19. Mode-shapes of two-way spanning CLT panels (UíChúláin et al., 2016).