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Erratum: Wood Design FOCUS (Volume 28, No. 2 Summer 2018)

Improving the Accuracy of Wood Diaphragm Deflection Estimates - An error was discovered on page 43. An important equation variable is improperly defined. The paper's derivation proceeds correctly, but users will obtain incorrect results.

The definition for k (found in the upper left column) should read as follows:

$k = S_{\perp}/S_{\parallel}$ (ratio of edge nail spacings)

Editorial

Industrialized wood building is on the rise. For example, the permanent modular construction industry has grown from 2.5% to 3.5% of the total construction industry in the past 5 years. Over 70% of the modular manufacturers in the US are light wood frame structured chassis factories. Much of this growth can be attributed to the increase in demand for low-rise multi-family and hospitality. Mass timber manufacturing factories are being planned in many parts of North America as research and development continues to bound. This issue is the second part of a series on industrialized wood construction, a movement to modernize the design and construction delivery process. Part 1 of this series focused on light wood platform frame construction. Part 2 includes topics related to mass timber construction.

The first paper of the series is from Schreyer and Clouston, University of Massachusetts Amherst professors. The paper is a case study of the J.W. Ovler Design Building at the UMass campus in Amherst. The building is an 87,600 square foot structure that features wood-concrete composite systems, off-site construction principles and serves design and construction students with its spaces and exposed structure and services. The paper examines three specific areas of industrialized wood construction: the hybrid glulam-steel "zipper" truss, the cross-laminated (CLT) shear cores, and the CLT-concrete composite panel system.

The second paper is from Hairstans, Plowas, Calcagno, and Milne, researchers from Edinburgh Napier University in the UK and Construction Scotland Innovation Centre. The researchers work in the Centre for Offsite Construction and Innovative Structures and perform research on timber resource compatibility from native and exotic wood species. This paper reports on the findings from a supply chain integration, pilot manufacture and quality assurance assessment of CLT made out of hardwood species, Tulipwood. The study was supported by the American Hardwood Export Council industry and academic collaborative demonstration project 'MultiPly' – a CLT pavilion exhibited at the London Design Festival in 2018. The findings include CLT manufacturing efficiencies with alternative species, shorter press time and the application of primer for hardwoods. The results indicate that Tulipwood CLT is a viable alternative for softwood CLT in cases of enhanced structural performance and aesthetic requirements.

The last paper, by Hindman from Virginia Tech and Memari of PennState, provides a brief overview of CLT as a building material, market penetration and potential for growth. However, the paper primarily focuses on examples of building sub-systems where CLT panels may be substituted for conventional panels. The two areas investigated in this paper include CLT for shaft enclosures and for curtain wall systems. The authors outline the technical opportunities and challenges associated with CLT employment in these situations with accompanying illustrations and details.

We hope you find this issue of *Wood Design Focus* informative. As always, comments and questions are welcome.

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Dear Wood Design Focus Reader, *It is with mixed emotions that I share I am stepping away from the WDF Editorial Board. It has been a pleasure serving on the board for many years and I have grown tremendously from the experience. WDF has a rich heritage of providing practical and timely wood engineering topics from a broad range of talented experts in the wood products industry. I trust that it will continue with excellence under new leadership. I am now with the International Code Council and my contact information is below. Feel free to reach out if you are so inclined.*

- John "Buddy" Showalter, P.E., Senior Staff Engineer, Product Development, International Code Council
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J.W. Olver Design Building A Case Study of a US Mass Timber Building

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Abstract

The University of Massachusetts, Amherst recently constructed the John W. Olver Design Building, a four-story, 87,600 ft^2 (8,100 m^2) structure which is today still one of the first institutional buildings in the US to employ engineered mass timber. It is also a showcase example for wood-concrete composite systems, off-site construction principles, and has become a teaching tool for explaining this type of construction to professionals and their next generation - students at UMass - which are being educated right within this structure.

This case-study article examines three specific components of this building that all espouse off-site construction principles often in combination with on-site additions: the hybrid glulam-steel "zipper" truss, the cross-laminated timber (CLT) shear cores, and the CLT-concrete composite panel system. These comprise the core of the structural system and offer many lessons for similar buildings.

Introduction

In early 2017, the University of Massachusetts Amherst opened the 87,600 ft^2 (8,100 m^2) John W. Olver Design Building. This building was designed to co-locate four built environment disciplines: the Building and Construction Technology (BCT) program, the department of Landscape Architecture and Regional Planning (LARP), as well as the department of Architecture. Situated near an important gateway to campus, this building was envisioned by its future occupants to be a showcase for advanced building and landscape design, and construction methods. Its visionary centerpiece is unquestionably the contemporary heavy-timber structure which demonstrates leading-edge timber engineering and wood architecture not only to the students who study there but also to the campus audience and broader design community of the region. Being a showcase structure, this building has become a teacher on campus in its own right.

The multi-year planning process for this $52M building was led by Boston-based architecture firm Leers Weinzapfel Associates, whose former projects include the MIT Media Lab and many other university and public buildings in the Eastern US. During this planning process, the future occupants requested various visionary and sustainability-minded building features such as bioswales, roof gardens, ample daylighting, and the aforementioned wood structure.

Current construction on the UMass Amherst campus, however, typically entails frame structures with steel deck and cast-in-place concrete floors, and bracing for lateral resistance. Stair and elevator shafts are often concrete block masonry, and walls are light-gauge steel, often with a clay brick or aluminum curtain-wall facade. Beyond the pre-cut steel, building elements are by-and-large fabricated on site. These materials and methods were also the typical choice for Leers Weinzapfel Associates in their previous buildings.

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As a result, the Design Building was originally conceived "by default" as a steel-frame structure and consultants (especially the structural engineer) were selected with this in consideration. Nevertheless, the historical context at UMass and in the region features many wood frame houses, heavy-timber buildings, and even wooden road structures such as covered bridges. It is in this historical context and in support of UMass' and our academic programs' sustainability goals that a massive wood structure for the Design Building was proposed.

While originally dismissed as infeasible due to the higher cost and Massachusetts' procurement laws, the authors of this paper and others insisted, provided contextual data, explained the many benefits of building with wood, and pushed for a cost comparison. While educative in its own right, this cost study did not provide enough accuracy for decision-makers to greenlight the wood structure. It was only when former congressman John W. Olver intervened and argued that this structure and the use of wood could support the rural forest economies in Massachusetts, that a $3M guarantee was put in place by the legislature. This additional contingency fund, along with the will to make the building a demonstration structure, ultimately swayed the university to proceed with the wood structural option.

Once this decision was made, the initial structural engineering firm was bought out of the contract and replaced with Equilibrium consulting, of Vancouver, Canada, an expert in wood structures (with Simpson, Gumpertz, and Heger as local engineer of record). Likewise, a structural erector needed to be found who had to be unionized to satisfy requirements put in place by the construction manager (Suffolk Construction). To guide the erector, a wood construction expert was also hired in a consulting role.

The Olver Design Building is a four-story structure on an angled, O-shaped plan (Fig. 1). It features a sloping roof over half of its plan and a roof garden at the center on the third floor level directly above an interior atrium. The structure consists of glulam columns and beams on approximately a 25′ x 25′ grid with wood-concrete composite floor decking spanning between beams. The roof garden is supported by a trussed-beam system (a "zipper truss") with the longest span of 55 ft, which itself rests on a two-story tall steel truss. Lateral resistance is provided by visible bracing in the south-west corner and structural CLT shear wall shafts (elevator and stairs) in three other locations. All interior and exterior walls are light-gauge steel, which was necessary for exterior walls due to the requirement in the IBC 2012 for non-combustible exterior walls in a Type IV-HT structure. The facade consists of a light-weight aluminum rain-screen panelized system.

Figure 1: The J.W. Olver Design Building at University of Massachusetts, Amherst

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Highlights of pre-manufactured components

All of the structural members (glulam, CLT, and steel) were CNC cut at the Nordic factory (and steel subcontractors) in Quebec, including all connections, which consisted of drift pins, slotted steel plates, glued rods, base plates, and similar. This allowed those to be assembled quickly and without much effort. Tight-fitting drift pins were inserted without much force and glued threaded rods at column bases fit easily into pre-drilled holes in baseplates. CLT floor and shear-wall plates were mainly site-fastened with long, full-thread screws that only required minimal pre-drilling.

Of the other building components (interior and exterior walls, the basement, etc.) only the aluminum facade panels were manufactured (and anodized) off-site and then simply attached in-place on site.

The structural system features prominently in three major building components that will be highlighted in the following sections (the "zipper truss", the shear cores, and the wood-concrete flooring system)

Hybrid Glulam-Steel Zipper Truss

The layout of the building wraps around a central courtyard. During the design process, various alternatives were evaluated and ultimately it was decided to create a "cloistered" interior roof garden at the third level which would be easily accessible and visible from faculty offices as well as studios. At the same time, this created a two-story tall interior atrium which would serve as a common space (or traditional New England "commons") in the core of the building: it was designed with a ramp, tiered seating, and a single-run, folded staircase on one side made of highly visible CLT panels which was intended as a sculptural feature (Fig. 2).

Figure 2: The Building Commons

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The roof garden was planned to support assembly functions (e.g. classes), needed to showcase intensive and extensive green roofs, and had to support Amherst's snow load, all while varying in span from 31 ft on its East end to 55 ft on its West end.

The design process involved intense collaboration between the architects, the structural engineers, and the landscape architects, which in turn became an early manifestation of the academic collaborative spirit that the building was intended to create. After many design iterations, the deeper soils were relocated to the East end where the spans were shortest. The West end now features decking and seating and all deep planters are confined there to the edges so that heavy soil loads would not be located at mid-spans.

The decking consists of short CLT panels, in a wood-concrete composite configuration. This also creates a concrete "pan", which helps with moisture protection and provides an additional safety barrier (besides the roofing material) between the green roof and the wood structure. Nevertheless, in this case, a *wet* green roof is being supported by a *dry* wooden structure.

This roof layout is supported by a set of seven trussed beams, the "zipper truss": a highly visible and educative showcase for various off-site fabrication methods. In addition to CNC-cut glulam, the truss consists of turned glulams for the diagonals, which themselves feature custom designed, cast steel end connectors that engage cut and welded steel plates at each end. The entire ensemble is completed with off-the-shelf BESISTA® tension rods and a custom cast steel "bullet" node connector as well as Glulam end connectors by CAST CONNEX®.

Figure 3: Zipper Truss Connection Components: Turned Glulams with Cast Steel End Connectors (top left), Cast Bullet Node (top right), Partially Assembled Truss (bottom left), Completed Truss Assembly (bottom right)

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The zipper truss was assembled in place, starting with the large hangers and beams, and followed by the CLT decking, diagonals, and the rods. The node element was installed last at which point everything could be connected using large steel pins, and tightened. Upon removal of the temporary shoring, no deflection was observed, proving the high stiffness and efficiency of this structural element.

Cross Laminated Timber Shear Cores

Lateral resistance of the North and East half of the Design Building is provided by seven-layer CLT shear walls at two stair shafts, one elevator shaft, and four service shafts as shown in Figure 4. These shear walls typically consist of continuous CLT panels over three stories with CNC pre-cut openings for doors and service/structural penetrations. In addition, one-story CLT panels were spliced-on at one stair location and the elevator shaft where the building rises to a fourth story. This was necessary because the four-story panel length exceeded manufacturing and transportation abilities.

Hold-downs at the base of these shear walls were custom designed steel brackets that connected to the vertical CLT panels via three rows of glued-in fasteners (HSK connectors by TiComTec®), which varied in length from 5.5 feet to 10 feet. These hold-downs then connected to Dywidag rods that were set into the foundations. Panel-to-panel connections typically consisted of long full-thread screws inserted either perpendicular or at 45-degree angles. Drag strut connections (and thereby force transfer) between beams and the shaft panels typically employed several rows of timber rivets to provide a low-slippage connection.

As with all glued connectors in this building, the hold-downs at the shear cores were factory installed and shipped with the panels. This was done to minimize any weather impacts and provide easier quality control for the gluing process.

Figure 4: CLT Shear Cores: Stair and Elevator Shafts (left), Glued-in HSK Connector (right)

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While all shear panel openings were typically CNC pre-cut, it was found that thorough coordination is crucial to enable this, especially as it pertains to upper-story mechanical penetrations. During the progression of the planning and procurement process, structural procurement needed to occur after only the lower floors had complete MEP coordination. As a result, some upper floor ductwork penetrations had to be cut on-site after the CLT panels had already been installed.

Cross Laminated Timber – Concrete Composite Flooring

The second and third story floors of the Design Building comprise of a 4 inch thick cast-in-place concrete slab on top of five-layer CLT panels with a one inch layer of polystyrene in between the concrete and the wood for sound attenuation. The concrete slab is integrally connected to the CLT with metal shear connectors (HBV connectors by TiComTec®) that are installed half-depth into the wood and half-depth into the concrete to enable the wood and the concrete to act as one composite section, similar to composite steel-concrete decks.

Researched by the authors in various journal articles (Clouston et. al. 2004 & 2005; Clouston and Schreyer 2008; Al-Sammari et. al. 2018), the connector is widely regarded as one of the most effective in providing superior floor stiffness and vibrational performance. This is in large part because the connector is glued into a rout in the wood with a stiff two-part epoxy limiting horizontal slippage between the concrete and the wood. Although the gluing process can be performed on-site (as is done in some European projects), the connectors were pre-installed in the CLT at the Nordic plant and delivered to site as an assembly. Figure 5 shows the assembly being craned into place.

Pre-installing the connectors into the CLT ensured consistent quality of the joint (particularly given a temperature and moisture sensitive adhesive) and took significantly less time to fabricate than if it were done on site. There were some minor challenges associated with the glued-in connector assemblies: to avoid damage during shipping of the unsupported metal connectors, the panels were stacked on the truck with cribbing. Also, the sharp edges of the connectors presented safety concerns for the workers, which was solved by covering the sharp edges with plastic tubing that was removed before the concrete slab was poured.

Figure 5. Installation of CLT Panels with Pre-installed Metal Shear Connectors

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Lessons Learned

The John W. Olver Design Building was envisioned as a showcase for contemporary wood construction as a feasible and sustainable solution in the context of the US Northeast. It was also intended to become a teacher in its own right that educates not only those involved in its construction (the architects, consultants, and builders) but also its occupants (the academic programs, our faculty, and students). It has delivered on both of these promises beyond expectation, which is evident by the continued high level of interest from professionals, students, and the general public.

There were many lessons learned during the planning and execution of this building. Some of the key lessons are summarized here:

- Despite our building's non-rectilinear architecture and several potentially cost-increasing features (story overhangs, a single large steel truss, a showcase zipper truss, a roof garden), overall project cost only increased from \$50M to \$52M when the project was switched from steel to wood (a 4% increase). This clearly illustrates that wood can be a cost-competitive choice if project design, procurement, and execution are well planned by a team that includes consultants with a thorough knowledge of the material wood. It can be expected that a similarly-sized building with a larger number of repetitive elements and less showcase features can be built at a cost that is at par or even lower than steel.
- A well-conceived wood based (glulam and CLT in our case) and CNC-prefabricated structure assembles efficiently and quickly, which can lead to faster construction progression and weather enclosure. Even if only the structure is installed in this way, subcontractors can move into a covered space and progress quicker. While this building did not use prefabricated exterior walls due to code limitations, the most recent building code makes these a possibility as well.
- A CLT-concrete composite floor deck system allows for column grids of 25 feet and beyond, which makes a wood structure competitive with steel structures. In addition, the combination of a glulam post/beam system with CLT-concrete decks removes the need for cross-beams, which are commonly placed every 10 feet in steel structures. This permits easier installation of MEP/HVAC systems and can reduce floor-to-floor heights. It is, however, imperative that structural and MEP coordination considers this early on in the planning process.
- With structure equalling finish for many wood surfaces (especially in the case of the columns, beams, CLT slab undersides, and the stair shaft insides), protection of these surfaces during construction (e.g. during concrete pouring) is required (which incurs small additional costs). Protection of wood surfaces against premature greying by sunlight is also important. In our building, most interior columns and CLT slabs were protected due to the quick progression of structure erection. However, columns and braces at the perimeter remained exposed longer and are showing the highest amount of appearance change (which required some additional sanding and refinishing).
- In-process coordination between architecture, structure, and MEP/HVAC is crucial for any off-site construction (unless those can be fully separated from each other). Even with a thorough and BIM (Building Information Modeling) based process, it is possible that the progression of the planning process may lead to a disconnect between those, which can cause delays or may require site-build solutions.

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The Quality Assurance of Tulipwood Cross Laminated Timber (CLT) for "Multi-Ply"

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Abstract

This paper presents the findings from the supply chain integration, pilot manufacture and quality assurance assessment of CLT made out of hardwood species, Tulipwood. The research was carried out as part of the American Hardwood Export Council industry and academic collaborative demonstration project 'MultiPly' – a CLT pavilion exhibited at the London Design Festival 2018. The research work demonstrates how CLT manufactured utilising alternative species can be piloted, quality assured and ultimately showcased via an engineered timber sculpture. The collaboration process implemented identifies areas for further investigation for full scale commercial production. In particular shorter press time and the application of primer for hardwood are highlighted given these would impinge upon productivity within full scale commercial production facilities. However, Tulipwood CLT is demonstrated to be a viable alternative to softwood CLT particularly where there are enhanced structural and aesthetic requirements.

Introduction

'MultiPly' (Figure 1) is the result of collaboration between American Hardwood Export Council, industry and academia. The purpose of the project was to deliver further information on the market potential for Tulipwood cross laminated timber (CLT) and combined with the rising movement of pre-fabricated and modular housing, raise the public profile of opportunities for market growth and potential for supply chain integration.

The Multi-Ply structure comprised 17 interconnected modules, made from a total of 102 60mm and 100 mm thick x 2.6m long cross laminated timber panels. 'MultiPly' pavilion was developed with a design for manufacture and assembly plus disassembly approach (DfMA+D). All joints and openings of the modules were precisely cut using CNC machines and connected using bespoke connections. The DfMA+D approach allowed the structure to be delivered 'flat packed', assembled in less than a week and disassembled after the exhibition was over with the possibility of re-constructing the 'MultiPly' structure in different locations.

Tulipwood used for the CLT manufacture is a hardwood and one of the most prolific in the U.S. and is unique to North America. Tulipwood is dimensionally stable at low moisture content, which makes it a suitable material for engineered timber products including CLT (AHEC, 2009). In addition, the aesthetic characteristics of Tulipwood make it particularly attractive for use as an exposed CLT. However, the manufacture and utilisation of hardwood CLT for structural applications has to date been relatively limited. AHEC have undertaken previous exemplar projects utilising tulipwood for solid laminate timber systems such as the 'Maggies' Centre for Care in Oldham (CLT). The CLT in the Maggies Centre was non-structural and the GluLam manufacturing process was not fully reflective of the manufacturing process to be utilised on this occasion.

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Correspondingly a quality assurance process was implemented particularly given the necessity to establish a pilot supply chain for the manufacturing process that isn't consistent with the commercial manufacture of CLT for the volume market.

Figure 1. "MultiPly" - a modular cross laminated timber pavilion made out of Tulipwood (Ed Reeve, 2018)

Hardwood CLT

Today, CLT is almost exclusively made of softwoods, however, the use of hardwood for the manufacturing of CLT is an object of growing interest. One of the main reasons for that is the superior mechanical properties of hardwood which could be of use in situations where higher load carrying capacity is required (Espinoza and Buehlmann, 2018).

Despite the increasing attention towards hardwood CLT, the research on this material is still scarce. Moreover, European CLT standard EN 16351:2015 "Timber structures – Cross laminated timber – Requirements" address exclusively softwoods as lamination material. The demonstration project presented in this paper aims to further expand the current knowledge on the topic and to demonstrate that hardwood CLT is a viable option capable of satisfying the requirements set in current regulations, including end product quality and mechanical performance.

EN 16351 stipulates specific criteria for the performance and production requirements of CLT. The compliance of cross laminated timber with the requirements of the standard required to be demonstrated by declaration of appropriate mechanical properties, bonding strength, resistance and reaction to fire, dimensional stability, release of dangerous substances and durability. Moreover, the CLT manufacturer is obliged to adhere to specific production requirements, some of the most important include:

- maintaining appropriate air temperature and relative humidity during production – at least 15°C (18°C during curing of the glue lines) and 40%-70% (at least 30% during curing) relative humidity;
- moisture content of the lamination should be between 6% and 15% (subject to adhesive manufacture recommendation);
- all laminations shall be planed to a tolerance level of ±2mm or 2% of the nominal board thickness at least 24h before bonding;

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The intention of this pilot manufacture was to implement the above conditions as much as possible to ensure the integrity of the CLT produced for ‘MultiPly’ as well as to provide an insight of the potential for full scale commercial production of CLT from Tulipwood.

Supply Chain and Process

There is no commercial volume producer of CLT in the UK. In addition, the manufacture of the CLT from Tulipwood for Multi-Ply was of a relatively small volume and in a sense bespoke for the purposes of the exhibition. However, via preliminary conversations between AHEC and an Edinburgh based organization Timber Design Initiatives it was identified that the product could be manufactured in Scotland via the instigation of a supply chain arrangement with necessary quality assurance conducted by an academic research partner. All project stages are summarized in Figure 2.

	Project Stage	Organization responsible	Deliverables
1.	**Architectural Design**	Waugh Thistleton Architects	Developed a working design of the CLT pavilion
2.	**Engineering Design**	Arup	Provided structural engineering appraisal
3.	**Raw material supply**	American Hardwood Export Council	Supplied and organised the transport of raw material
4.	**Raw material processing**	Glenalmond Timber Company Ltd.	Defect-cutting, finger-jointing and planning of raw
	QA test work (CLT boards)	Edinburgh Napier University	Acoustic characterisation and strength testing of finger
5.	**CLT manufacture**	CS-IC Innovation Factory	Pressing and post-processing of CLT panels
	QA test work (CLT panels)	Edinburgh Napier University	Structural assessment of CLT panels
6.	**CNC machining and Assembly**	Stage One	Module joints fabrication and erection of Multiply

Figure 2. Flowchart illustrating the partners and their role in the delivery of “MultiPly”

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With respect to the quality assurance of the material for CLT manufacture the following additional points are made:

- Material shipped from the US included timber of varied quality, Glenalmond Timber (a Scottish lumber importer and processor) visually graded the boards to a General Structural Temperate Hardwood (TH1) grade.
- The lamellae for CLT production were sawn into two standard widths (95 and 145mm) to maximise yield and ensure a consistent arrangement of the material.
- Widths were defect-cut and finger jointed to lengths specified by project architects Waugh Thistleton and engineers Arup.
- The MTG acoustic timber grader was utilised to acoustically characterize the resource and a sub-set was also structurally tested in order to verify results.
- Structural testing of the finger joints was undertaken on a sample range to ensure structural robustness.
- Additional structural testing of a sample range of fabricated panels was conducted in accordance with EN 16351 including: bending with in-plane and out-of-plane loads, rolling shear, delamination and bonding strength demonstrating the structural integrity of Tulipwood CLT.

Tulipwood CLT Manufacture

Following the raw material processing the boards were transported to the Construction Scotland Innovation Centre (CS-IC) Innovation Factory, 61 miles away, where the Tuliwpood boards were pressed into the CLT panels used to construct 'MultiPly'. The structure required a total of 102 panels which were manufactured in 25 days.

The pilot production process was set-up in manner to best replicate full scale commercial production (Table 1 and Figures 3 to 4). All manufactured panels, comprised of 3 and 5no. 20mm Tulipwood lamellas of various widths, were produced in accordance with EN 16351 using a Woodtec Fankhauser vacuum press.

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Table 1. Tulipwood CLT Production Process

Stage	Info
Environmental Control	• The CS-IC Innovation Factory was heated but there are no means to control humidity. • To ensure that the requirements set out in EN 16351 are fulfilled, the temperature and humidity was checked using a thermo-hygrometer throughout the entire CLT manufacture and results recorded on a standardized CLT production record. • During production, recorded temperatures were between 17˚C - 26˚C and relative humidity between 38% - 78%.
Planning	• All timber was supplied PAR (planed-all-round) and cut to length at 20x95x2700 or 20x145x2700mm. • The temperature and moisture content of randomly selected lamellas was measured using a moisture meter equipped with temperature probe. • According to the production records the moisture content of the boards was between 8% and 9%.
Priming	• All glued faces of the lamellae were primed prior to assembly. • The primer concentrate (Henkel Loctite Purbond PR 3105) was mixed at a ratio of 9 parts water to 1 part primer concentrate and uniformly applied to all surfaces that were to be glued. • Following the recommendation from adhesive manufacturer the primer was applied within 6 hours of lamellae being planed and all primed lamellae were be bonded within 6 hours of being primed.
Laying Up and Adhesive Application	• During the production the first layer of lamellae was placed longitudinally in the bed of the vacuum press ensuring that any gaps between the edge faces of the lamellae are kept to a minimum. • Adhesive (Purbond HB S609) was applied at the rate of 170g/m^2 • To ensure full coverage and consistent glue application the adhesive gantry traveled from the top to the bottom of the press at a uniform rate. • All subsequent layers of lamellae were laid up perpendicularly to the previous layer and the adhesive applied in the same manner until all plies were laid up
Pressing	• Once all lamellas were laid up, two hydraulic rams were located along the top edge of each panel at nominal 900 mm c/c. • Load was continually increased until all gaps between lamellae were removed from the lateral layers. • The vacuum sheet was then brought across the entire press and clamped around the perimeter. • Once the sheet was secured the vacuum pump was turned on with the pressure set to 150 mbar. • The vacuum reached full pressure within 60 minutes of the adhesive first being applied and was left on for a minimum period of 300 minutes (twice the amount of time required for softwoods).
Storage	• After 5 hours of pressing time each panel was removed from the vacuum press in a flatwise orientation using the overhead gantry crane and stored in the same environment for at least 10 hours.

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Figure 3. Application of PUR adhesive

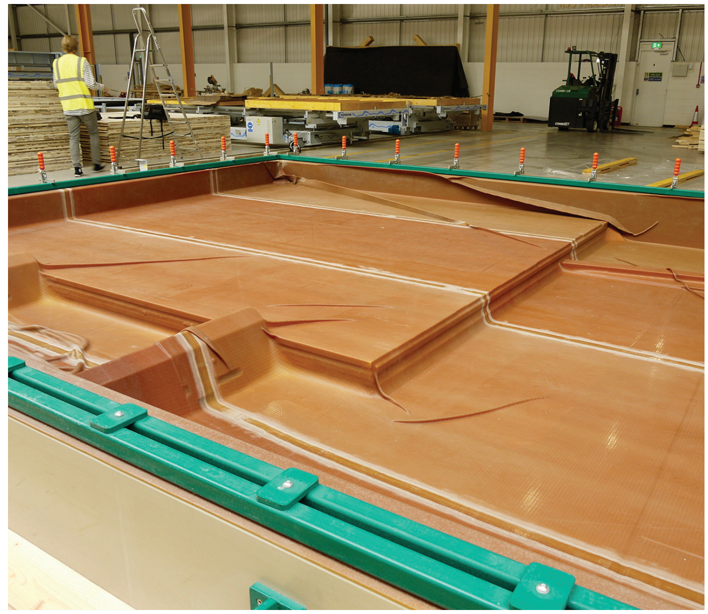

Figure 4. Application of bonding pressure

The material processing, CLT manufacturing and quality assurance approach was implemented successfully ensuring the structural integrity of the Multi-Ply project. The approach taken also identified particular requirements for hardwood CLT production including the requirement for primer application and increased press time.

Conclusions

The use of hardwood timber species for the production of CLT represents an opportunity to add value to the resource. The formation of a CLT slab serves to enhance the properties of a structural element via re-engineering the baseline performance of available material and create larger structural components primarily for wall, floor and roof applications. However, the current standards for CLT production are set for softwood species and there is little available information on the use of hardwood. Further, the utilisation of alternative species such as Tulipwood for CLT production is restricted as a result of manufacturing conformity requirements such as the necessity for primer application. Integrating with the current supply chain is therefore difficult and for pilot case studies restricted further given the current global demand for CLT utilising the capacity of most volume manufacturers. Therefore, in order to pilot manufacture for demonstration projects it may be necessary to set up a localised supply chain and recreate as much as practically possible commercial production instigating a high level of quality assurance to ensure structural robustness.

This project implemented the pilot production of Tulipwood CLT for the 'MultiPly' pavilion exhibited as part of London Design Festival 2018 as well as demonstrated the compatibility of Tulipwood with the CLT production process. The process implement could be replicated for further projects where the pilot production of CLT is to be used for structural purposes. However, to fully optimise the performance and production process, prior to the commercialisation and certification, follow-on analysis and additional test work is recommended and this could be run concurrently with a follow-on project working via the same process or in collaboration with a full scale CLT manufacturer. In particular, the time constraints set out by the adhesive manufacturers regarding recommended press time and the application of primer, are of specific interest. In this pilot project adhesive was applied at 170gm/m^2, compared to the 130-150gm/m^2 typically used for softwood

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CLT, and the press time was doubled. Having more knowledge on the influence of primer and pressing time on the structural integrity of hardwood CLT would potentially lead to further optimisation of the manufacturing process which would be of importance from a productivity and corresponding commercialisation perspective.

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Mass Customized Cross-Laminated Timber Elements for Building Construction

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Introduction to Cross-Laminated Timber

Cross-laminated timber (CLT) is a new building material being used in the United States construction industry. The architecture, engineering and construction (AEC) community has shown great interest in the use of CLT construction methods. According to a report by Zion Market Research, the North American CLT demand was around $130 million in 2017 and is expected to grow, with an overall global growth rate of 15% per year until 2024 (Zion Market Research, 2018).

The current CLT building style consists of a set of exterior load-bearing walls with the addition of interior bearing walls for buildings of greater heights (Green 2012). CLT construction has been used for a range of building types, from residential, educational, commercial and light industrial. Currently, the tallest CLT building is Brock Commons, an 18-story dormitory at the University of British Columbia in Vancouver, British Columbia, Canada (Connolly et al. 2018). However, a 21-story CLT building has just passed plan approval in Milwaukee, Wisconsin as of January 2019 with expected completion by spring of 2021 (Daykin 2019). A distinct advantage of CLT construction methods is the quick assembly time – Brock Commons needed less than 70 days for completion (Woodworks, 2019).

Cross-laminated timber as a structural building material has proven its value based on the recent construction of various large-scale buildings throughout the United States. The appeal of CLT is very multi-faceted. First, this is the first truly two-dimensional massive structural element available in the area of timber products, allowing an increased use and flexibility of design and construction. Another advantage is the ease of connection of CLT panels using metal plated connectors and self-drilling, self-tapping screws. These connections also allow CLT members to be easily attached to steel elements and integrated into the design. From the construction viewpoint, an advantage of CLT is the modularity of design and ability to complete most of the construction preparation of the panels off-site. This tends to lower construction costs and delivery times since the only on-site operations are lifting and installation of the panels, which is facilitated by interlocking connections and self-drilling, self-tapping screw connections.

In a recent article in the University of Washington alumni magazine (Duff 2017), the benefits of CLT construction were expounded upon to produce light, efficient, carbon friendly buildings. Perhaps the greatest advantage of CLT construction noted was the revitalization and job growth in many rural areas where forest resources exist and employment is scarce (Duff 2017). Much more than just a building material, CLT is viewed by many as an economic force. Many CLT production facilities in the United States are being placed in timber-rich portions of the country to provide rural economic development.

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The appeal of CLTs as low-carbon buildings, while not canonized in the United States building requirements, has been a major influence on CLT construction in Europe and continued focus on low-carbon structure initiatives will give CLT an advantage over other materials. Zion Market Research notes that the increased use of CLT is in part related to desires for sustainable construction (Zion Market Research 2018).

Offsite Construction Methods

Offsite, or pre-manufactured, or prefabrication systems refer to elements of buildings produced off-site, then transported and assembled on site (Pasquire 2002). Pre-manufactured systems can vary from assemblies of individual components (trusses, walls, roofs) (Generalova et al. 2016) to three-dimensional assemblies complete with plumbing, electric and finish trim (O'Brien 2000). Benefits of pre-manufactured construction were examined by a survey of building professionals in Hong Kong, who rated (in order of preference) better supervision, consistent design from early stages, reduced construction costs and shortened construction time as the most beneficial assets (Tam et al. 2007).

An essential component of the successful integration and use of pre-manufactured elements is building information modeling (BIM), which unlike 3D CAD system, allows data and attributes of model elements to be incorporated into the model, providing specific information about the components and assemblies used (CRC Construction Innovation 2007). Lu and Korman (2010) presented several case studies of how BIM can be implemented in modular and pre-manufactured construction projects.

Offsite Construction Using CLTs

The prefabrication benefits of CLT have been highly espoused, allowing construction of unitized systems and assemblies (Kremer 2018).

With the stated vision of using CLT as an economic driver, the question was raised about how the economic profile of CLT materials could be expanded further in the area of construction. As CLT enters the building code and market to a higher degree, it may be helpful for us to reevaluate current uses of conventional materials and understand how CLT can be incorporated or substituted to produce more efficient structures in terms of time and labor. The intent of this article is to start a conversation about different uses of CLT materials in building subsystems. Several examples of building subsystems are suggested.

Examples of CLT Building Sub-Systems

Shaft Wall Systems

Shaft walls are continuous wall systems which penetrate through several floors to provide access (elevators, stair cores) or services (MEP shafts) to the building. Several resources for the design of wood-based elevator shafts are available from Woodworks (McLain n.d.) and discuss the design and construction methods of shafts.

According to the 2018 IBC, a shaft is defined as "an enclosed space extending through one or more stories of a building, connecting vertical openings in successive floors, or floors and roof" (§202) (IBC 2017). Provisions describing shaft enclosures are given in Section 713. Shaft enclosures are also constructed as fire barriers, which must conform to Section 707 as well. Furthermore, the materials permitted should conform to the type of building construction (713.3) and must have a fire rating of at least 2 hours when connecting 4 stories or more, or a fire rating of at least 1 hour when connecting less than 4 stories (713.4). An important quality of shaft enclosures is the idea of continuity of the fire barrier to prevent fire from entering the shaft or entering various floors that the shaft passes through. McLain (n.d.) provides specific details of wood construction to achieve fire barrier continuity.

A recent project at Trinity Western University in Canada used a CLT shaft wall for the elevator core system of a light-framed five-story building (ThinkWood 2019). The use of CLT for shaft walls

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of light-framed structures seems an ideal pairing given the greater shear strength of the CLTs to act as lateral bracing for the light-framed structure, possibly providing a reduction in shear wall lengths needed, and also allowing more architectural freedom in design.

A CLT elevator shaft was recently completed by Smartlam for a building in Whitefish, Montana in 2016 (www.forconstructionpros.com 2016, Smartlam 2016). Specific advantages of the use of CLT elevator shafts over more conventional concrete-masonry-units (CMUs) were given as dimensional stability, environmental performance, lower costs and quicker assembly. For this project, the CLT elevator shaft walls were assembled in several hours with three people and a crane. The equivalent sized CMU elevator shaft would have taken three weeks to construct using 8-12 people. Cost savings were estimated between 70 and 75%.

Curtain Wall Systems

In the majority of tall steel and concrete building systems, exterior bearing walls are not commonly used, but rather a non-load-bearing light gage steel framing located internally is used to reduce building weight and increase the usable square footage. These buildings rely upon curtain walls, relatively thin and light walls which "hang" from the building, similar to a curtain, and serve as the building envelope (BE) of the structure (Morris 2013). In general, BE systems can consist of windows, glass curtain walls, cladding panels of different material (e.g., concrete, stone, metal), and masonry or stone veneer, to name a few. (Memari 2015). BE systems can be subjected to environmental loads such as wind, rain, temperature change, and other structural loads such as self-weight, live load, column shortening, and earthquake effects.

Curtain walls encompass a wide variety of wall styles and materials, from panelized wall sections, to stick systems using light gauge steel panels and

Figure 1. Elevator Shaft Constructed by Smartlam (Photo Credit: Smartlam)

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some opaque or transparent infill panels. Most curtain walls consist of a frames made of steel studs or aluminum framing bolted or welded together and attached to the structural system of the building with some insulation material installed between the studs. As elaborated subsequently, outer layers of material are then attached to the curtain wall to prevent moisture intrusion, heat loss, and noise.

The previous discussion of curtain walls begs the question – could CLT materials be used to construct curtain walls? Thin CLT panels could be used to replace many of the unitized curtain walls where a system of metal studs and insulation are currently used. While these curtain walls include areas of glass panels, the solid panels surrounding the glass are the areas where CLTs could be used as shown in Figure 2. The development of CLTs for curtain walls systems would represent an additional material application of CLTs in an area where there is currently no forest product material used. Advantages of CLT curtain wall construction could include a lack of thermal bridging observed through the metal studs, better acoustic performance of the CLT panels (Golden and Wyrick 2016), better air-sealing of structure due to CLT joinery methods, and ease of construction due to the pre-cut nature of CLTs.

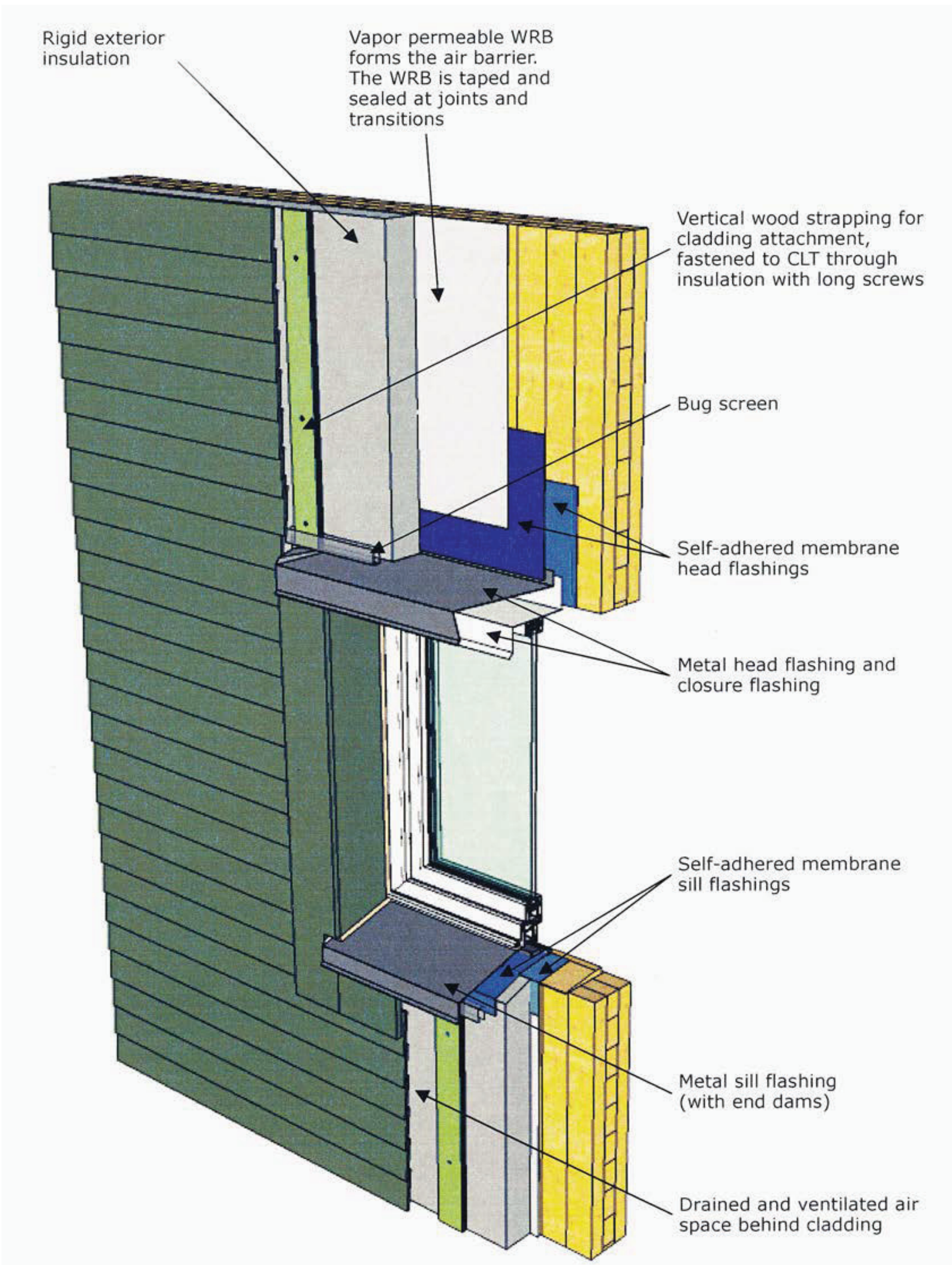

Figure 2.
Wall detail of exterior cladding materials over CLT wall (Glass et al. 2013)

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Regardless of the type of building envelope (BE) system chosen for buildings, such components are responsible for several functions such as providing heat, air and moisture flow resistance, daylighting and radiation control, sound insulation, as well as aesthetic features and satisfactory indoor air quality. Moreover, the BE will need to resist the gravity and lateral load resistance if it forms a load bearing structural system as in light-frame wall systems. Examples of such BE system include traditional wood stud frame, structural insulated panels (SIPs), and insulated concrete forms (ICFs) (Memari et al. 2014). CLT façades can easily be used as load bearing panels as in the case of other materials/ systems mentioned, or CLT façades could also be used as a non-load bearing curtain walls hung from the side of the building. Figure 3 shows a comparison of the two alternative uses.

fire resistance, sound insulation, and thermal mass properties, which is highly desirable for energy efficiency by absorbing heat during thermal heat gain hours and slowly releasing the heat to the interior during the cooler night climate. Some optional details for use of CLT as an exterior wall with insulation, moisture retarder and air barrier options are discussed by Glass et al. (2013), Finch (2018), Mayr Melnhof Holz (2013), and Byle (2012).

The major challenge then for CLT as a an exterior wall panel would be to be clad on the exterior side by other layers to provide control over environmental loads such as rain, air flow/leakage, heat and humidity transfer, and radiation (Glass et al. 2013). In particular, given the nature of panelized systems, special efforts will be needed to seal joints between CLT panels and between vertical CLT panels and horizontal floor/roof panels in order to create an airtight enclosure in order to lower energy loss and reduce the chance of condensation due to vapor transport through air leakage. Different technologies are available for this purpose, including joint tapes, membranes over the entire exterior side of the panels (self-adhered, liquid applied, and mechanically fastened), and flexible joint foam sealant. While applying joint tape or joint filler is acceptable, for a conservative heat loss and condensation control, some recommend application of membrane over the entire wall system (Glass et al. 2013)

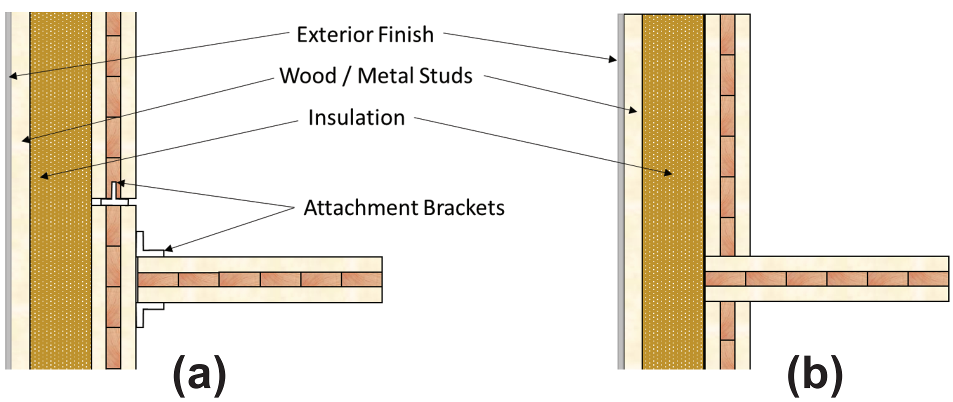

Figure 3. Comparison of the use of CLT Façade as (a) non-load bearing curtain wall, and (b) load-bearing exterior wall

The use of CLT in building façade or envelope system must follow guidelines for similar panelized wall systems, most relevant being SIP panels for having wood based (OSB or plywood) sheathing on both faces that sandwich rigid insulation. Of course, while CLT offers thermal resistance on the order of R-value of 1.25 per inch, which for an 8 in. thick panel, it will have an R-value of 10, this is about 1/3 of the R-value provided by the same thickness typical SIP panel (Insulspan 2019). Besides thermal insulation property, CLT also possesses

Besides thermal resistance and air tightness criteria for design of CLT BE system, protection against moisture is another significant design requirement. Given the thickness of CLT panels, and being a wood member, CLT can absorb large amount so moisture if exposed to bulk water or vapor flow. Considering that CLT will be clad by air barrier membrane and insulation on the exterior side and

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that it has low vapor permeability, any moisture absorbed by the panel will not easily dry out or dry in, and will be vulnerable to deterioration over time with potential for mold growth. Therefore, it is essential to allow CLT to dry in and dry out by using vapor permeable interior finish such gypsum drywall and have vapor permeable air barrier on the exterior. Furthermore, to minimize the chance of bulk water due to rain to reach the surface of CLT, a rainscreen cladding with a drainage plane and flashing system as shown in Figure 4 is needed that allows any potential moisture on the drainage plane to drain out through weep holes and flashing. Most US CLT projects using CLT bearing walls have employed rainscreen barrier systems to keep moisture away from the CLT panels.

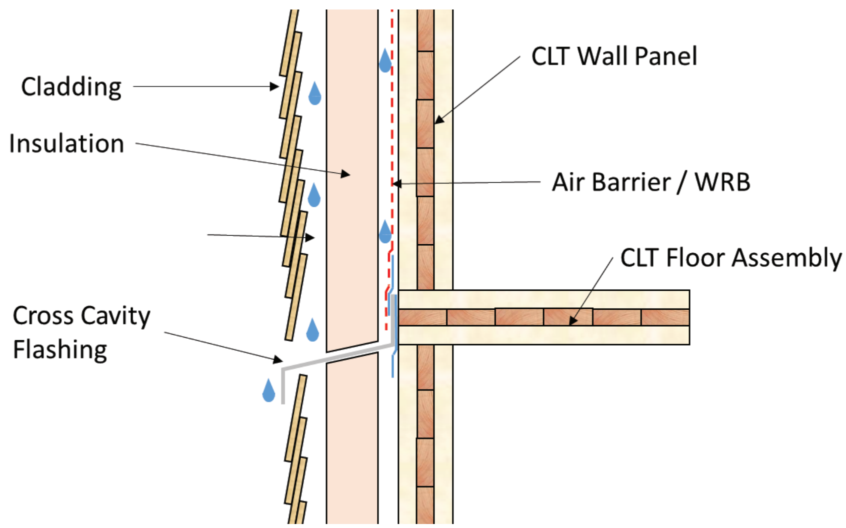

Figure 4. Detail of CLT Exterior Wall Showing Flashing and Vapor Barrier

When the CLT façade is part of the opaque part of strip windows with glass curtain wall used for glazing, the detail at CLT to window frame connection becomes crucial in order to avoid any moisture intrusion. In particular, careful detailing of a sloped flashing to direct water running off the exterior window surface away from the cladding, a sloped sill plate and properly arranged waterproofing membrane over the top of CLT and insulation among other details including upturned end dams will be necessary.

Summary

This article provides some examples of building sub-systems where CLT panels could be substituted for other conventional panels. For example, besides the already established use of CLT walls panels as substitute for masonry or concrete load bearing wall construction, this article reviewed the use of CLT panels for shaft enclosures. The design of shaft enclosures depends upon creating a fire rated assembly and maintaining the continuity of the fire barrier system throughout the height of the shaft enclosure.

Another example use of CLT panels that this article has shown is for curtain wall systems, and it has discussed in particular the building science challenges involved. The attachment of the curtain wall to the frame, moisture prevention, thermal systems must all be carefully considered in the design. The article demonstrates that the potential of using CLT panels for curtain walls is feasible, both as non-load bearing and load-bearing. However, the use of CLT curtain wall systems requires more extensive testing of the CLT elements as well as the particular curtain wall system configuration used. More detailed study and in particular testing of CLT panels for use as curtain wall systems is needed.

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