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Introduction to New Material - Cross Laminated Timber

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Abstract : ***Cross Laminated Timber (CLT) is the next step in the evolution of engineered wood building systems which has started gaining popularity in Europe and recently in North America. CLT is a prefabricated product made from 3 or more layers of industrial dried lumber, stacked together at right angles and glued over their entire surface. CLT offers high strength and the structural simplicity needed for cost-effective buildings, as well as a lighter environmental footprint than concrete or steel. It also provides numerous other benefits including quicker installation, reduced waste, improved acoustic; seismic; fire; thermal performance and design versatility. This cost competitive wood building system can be used in a wide range of applications, including mid-rise urban infill, industrial, educational and civic structures and also bridge decks. This paper briefly presents history, manufacturing process, advantages, applications, analytical design methods, mechanical properties and Code provisions of CLT.***

Keywords: CLT, Benefits, Applications, Analytical Design Methods and Code Provisions.

Introduction

Cross laminated timber (CLT) is the rising star of the global mass timber construction industry. Often described as 'pre-cast timber', CLT is a prefabricated engineered wood product consisting of not less than three layers of solid-sawn lumber or structural composite lumber where the adjacent layers are cross oriented and bonded with structural nontoxic adhesive to form a solid wood element. Material properties of CLT vary according to the manufacturer and basic materials. Wood that is used in production of CLT is normally spruce, but larch and pine may be available. The type of wood that is used for manufacturing of CLT affects bending and shear strength. The common strength grades (WIS 4-7) for the laminates are in the range C16 to C24 and at least one manufacturer offers 'glulam' grades GL24H to GL28H.Most manufacturers use formaldehyde-free interior/exterior polyurethane (PUR) adhesives. Boards are face-glued and then pressed, planed and sanded into panels. Using Computerized Numerical Control (CNC) machinery, the panels can be custom fabricated to create openings, compound angles and unique features requiring complex geometry to meet specific end-use applications.

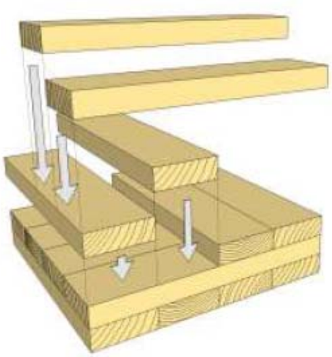

Fig. 1 Layup of CLT

It is an exceptionally strong product that provides dimensional stability, strength and rigidity and allows transfer of both lateral and vertical loads on all sides. Since CLT panels resist high racking and compressive forces, they are particularly cost effective for multi-story and long span diaphragm applications. They weigh less than concrete or steel; hence can also reduce foundation costs. In addition, CLT elements can be combined with other building materials such as glulam beams, enabling flexibility in design, style and finished architecture. While CLT panels act as two-way slabs, the stronger direction follows the grain of the outer layers. For example, when used for walls, CLT is installed such that boards on the outer layer of the panel have their grain running vertically. When CLT is used in floor and roof applications, panels are installed in such a way boards on the outer layer run parallel to the span direction. Because they are manufactured for specific applications, CLT panels are prefabricated and shipped directly from the manufacturer to the job site, where they can be quickly and efficiently lifted into place.

CLT panel sizes vary by manufacturer; typical widths are 0.6 m (2.0 ft.), 1.2 m (4.0 ft.), and 3 m (9.8 ft.) (could be up to 4~5 m (13.0 ~ 16.5 ft.) and length can be up to 18 m (60 ft.) and the thickness can be up to 508 mm (20 inches). A CLT panel is usually composed of an odd number of layers, generally 3, 5, 7, 9, 11. The general CLT properties are – Thermal conductivity 0.13 W/mK, density – 480-500 kg/m^3, Compressive strength -2.7 N/mm^2 (perpendicular to grain boards); 24 – 30 N/mm^2 (parallel to grain boards), Bending Strength – 24 N/mm^2 (parallel to grain boards) and modulus of elasticity – 370 N/mm^2 (perpendicular to grain boards); 12000 N/mm^2 (parallel to grain boards)

CLT Applications

CLT panels can be used for wall, floor, roof, curved roof and beams, made from a variety of softwood and sometimes hardwood species.It could have different cross section dimensions and layout of boards, and can be manufactured with various methods. Other applications of CLT panels are in bridge decks, and temporary applications such as crane rig mats and temporary road bases. The following figure shows various examples of CLT Structures.

Fig. 2Viken Skog, BA, Norway

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Fig. 3Murray Grove, London

Fig.4 Toronto Condominium Block

Fig.5 RaabstegFeldbach Bridge

Brief History

Cross-laminated timber (CLT) is an innovative wood product that was introduced in the early 1990s in Austria and Germany and has been gaining popularity in residential and non-residential applications in Europe. In the early 2000, construction in CLT increased significantly, partially driven by the green building movement but also due to better efficiencies, product approvals, and improved marketing and distribution channels.

CLT is a relatively new building system of interest in the North American construction and is helping to define a new class of timber products known as massive or "mass" timber. It is a potentially cost-competitive, wood-based solution that complements the existing light frame and heavy timber options, and is a suitable candidate for some applications that currently use concrete, masonry and steel.

CLT has many advantages which it offers to the construction sector. The European experience shows that CLT construction can be competitive, particularly in mid-rise and high-rise buildings. Easy handling during construction and a high level of prefabrication facilitate rapid project completion. This is a key advantage, especially in mid-rise construction (e.g., 5 to 10 stories). Lighter panels mean that foundations do not need to be large. They also mean that smaller cranes can be used to lift panels higher. Good thermal insulation, good sound insulation and good performance under fire are added benefits that come as a result of a massive wood structure. CLT popularity shows by worldwide sales have reached a figure of approximately 500,000 m^3 and several examples of CLT buildings up to 10 stories could be found around the world.

CLT Manufacturing Process

The first step for production of CLT is from the cross cutting logs. Then the process of grading and trimming of the boards is done to exclude the parts of the wood that have flaws such as knots, and checks. In this part the long members are formed up to 16 m of length. The next step is to make the panels from the finger jointed lamella, a method of connecting timber and wood members to make a continuous member. Finger joints are made of a set of complementary rectangular cuts in two or more pieces of wood which are locked and glued together. After making the finger jointed board members, they are edge glued to each other to make panels. The panels are also connected to each other using adhesives in perpendicular directions to each other. To attach the panel layers together; the face gluing is done, also a horizontal bonding pressure up to 0.6 MPa by hydraulic equipment is used to increase the strength of panels. The assembled panels are usually planed and/ or sanded for a smooth surface at the end of the process. Panels are cut to size and openings are made for windows, doors and service channels, connections and ducts using CNC (Computer Numerical Controlled) routers which allow for high precision.

Schematically the typical manufacturing process of CLT products involves the following nine basic steps:

1) Primary lumber selection, 2) Lumber grouping, 3) Lumber planning, 4) Lumber or layers cutting to length, 5) Adhesive application, 6) Panel lay-up, 7) Assembly pressing, 8) CLT on-line quality control, surface sanding and cutting, and 9) Product marking, packaging and shipping

Fundamentally, it is possible to produce any CLT thickness by combining the following layer thicknesses: 19 mm (3⁄4 in.), 25 mm (1 in.), and 38 mm (1.5 in.) up to maximum 50 mm (2 in.). The final CLT thickness ranges from 72 mm to 400 mm. Panel size is generally dictated by the press size. The width of CLT panels ranges from 0.5 m to 3 m, and may reach 5 m for certain applications. Some manufacturers produce CLT panels up to 18 m long.

The key to successful CLT manufacturing process is consistency in the lumber quality and control of the parameters that impact the quality of the adhesive bond. Usually, lumber must be kiln dried to a moisture content of 12% ± 3%, and commonly finger jointed into long boards before being assembled into a panel.

For quality control purposes, compliance with product requirements prescribed in the product standard are typically checked at the factory (e.g., bending strength, shear strength, delamination etc.).

CLT'S Key Advantages

Cost effectiveness: The weight of CLT is about 4 times less than concrete which reduces foundation loads and transportationcosts. In a 2010 study by FPInnovations, researchers compared the cost of CLT versus certain concrete, masonry and steel building types. While the advantages of faster construction time and lower foundation costs were not accounted for, the estimated cost of a U.S.-built CLT structure was found to be particularly competitive for mid-rise residential (15 percent less), mid-rise non-residential (15 to 50 percent less), low-rise educational (15 to 50 percent less), low-rise commercial (25 percent less), and one-story industrial buildings (10 percent less).

Design flexibility: It is relatively easy to increase the thickness of a CLT panel to allow for longer spans requiring fewer interior support elements. Manufacturers use CNC equipment to cut panels and openings to exact specifications, often to meet very tight tolerances (within millimeters). Plus, when field modifications are needed, they can be made with simple tools.

Fast installation: Panels are prefabricated, assembly time is greatly reduced, which improves efficiency and results in lower capital costs and faster occupancy. Wall, floor and roof elements can be pre-cut, including openings for doors, windows, stairs, service channels and ducts. Insulation and finishes can also be applied prior to installation, reducing demand for skilled workers on site.

Fire protection: CLT's thick cross-section provides valuable fire resistance because panels char slowly. Once formed, char protects the wood from further degradation. When used in Type IV construction, CLT assemblies also have fewer concealed spaces, which reduce a fire's ability to spread undetected. In addition, CLT offers increased compartmentalization if used for interior walls. The American Wood Council conducted successful ASTM E119 fire resistance test on CLT wall of 7 inches thick with maximum attainable load by test equipment. The test specimen lasted 3 hours, 5 minutes and 57 seconds.

Thermal performance and energy efficiency: CLT's thermal performance is determined by its U-value, or coefficient of heat transfer, which relates to panel thickness. Thicker panels have lower U-values; they are better insulators and therefore require less insulation. Since CLT panels can be manufactured using CNC equipment to precise tolerances, panel joints also fit tighter, which results in better energy efficiency for the structure. Because the panels are solid, there is little potential for airflow through the system. As a result, interior temperatures of a finished CLT structure can be maintained with just one-third the normally required heating or cooling energy.

Environmental advantages: Manufactured using wood from sustainably managed forests, CLT provides a number of environmental benefits in addition to its excellent thermal performance. Wood is the only major building material that grows naturally and is renewable, and life cycle assessment studies consistently show that wood outperforms steel and concrete in terms of embodied energy, air pollution and water pollution. It also has a lighter carbon footprint— because wood products continue to store carbon absorbed by the trees while growing, and wood manufacturing requires less energy and results in less greenhouse gas emissions. In fact, the architect of CLT building, UK, concluded that the carbon stored in panels and emissions avoided by not using concrete, kept 300 metric tons of carbons out of the atmosphere.

Less waste: CLT panels are manufactured for specific applications, which results in little to no job site waste. Plus, manufacturers can reuse fabrication scraps for stairs and other architectural elements, or as biofuel.

Seismic performance: Because of their dimensional stability and rigidity, CLT panels create an effective lateral load resisting system. Researchers have conducted extensive seismic testing on CLT and have found panels to perform exceptionally well with no residual deformation, particularly in multi-story applications. In Japan, for example, a seven-story CLT building was tested on the world's largest shake table (magnitude of 7.2 and acceleration of 0.8 to 1.2g). It survived 14 consecutive seismic events with almost no damage. CLT also offers good ductile behavior and energy dissipation.

Acoustic performance: Test results show that because the mass of the wall contributes to acoustic performance, CLT building systems provide adequate noise control for both airborne and impact sound transmission. CLT building systems offer additional acoustic benefits because builders use sealant and other types of membranes to provide air tightness and improve sound insulation at the interfaces between the floor and wall plates.

Structural Design Considerations of CLT: CLT panels are typically used as load-carrying plate elements in structural systems such as walls, floors and roofs. Lumber in the outer layers of CLT panels used as walls are normally oriented up and down, parallel to gravity loads, to maximize the wall's vertical load capacity. Likewise, for floor and roof systems, the outer layers run parallel to the longer span direction. For floor and roof CLT elements, key characteristics that must be taken into account are as follows:

Out-of-plane bending strength, shear strength, and stiffness

Short-term and long-term behavior: - Instantaneous deflection, Long-term deflection (creep deformation), Long-term strength for permanent loading

Vibration performance of floors

Compression perpendicular to grain issues (bearing)

Fire performance, sound insulation, exposure to elements

For wall elements, key characteristics that must be taken into account at the design stage include: Load-bearing capacity (critical criteria), In plane and Out-of-plane shear and bending strength, Fire performance, Sound insulation and Exposure to elements

Introduction to Analytical Design Methods used in CLTFloor, Roof and Wall Systems

Different methods have been adopted for the determination of basic mechanical properties of CLT in Europe. Some of these methods are experimental in nature while others are analytical. For floor elements, experimental evaluation involves determination of flexural properties by testing full-size panels or sections of panels with a specific aspect (span-to-depth) ratio. The problem with the experimental approach is that every time the lay-up, type of material, or any of the manufacturing parameters change, more testing is needed to evaluate the bending properties of such new products.

Obviously, the analytical approach, once verified with the test data, offers a more general and less costly alternative. An analytical approach generally predicts strength and stiffness properties of CLT based on the material properties of the laminate planks that make up the CLT panel.

The most common analytical approach that has been adopted for CLT in Europe is based on the "Mechanically Jointed Beams Theory" (also named Gamma Method) that is available in Annex B of Eurocode 5 (EN 2004).

Blass and Fellmoser have applied the "Composite Theory" (also named k-method) to predict some design properties of CLT. However, this method does not account for shear deformation in individual layers and is reasonably accurate for high span-to-depth ratio.

More recently, a new method called "Shear Analogy" (Kreuzinger) has been developed in Europe that seems to be applicable for solid panels with cross layers. The methodology takes into account the shear deformation of the cross layer and is not limited to a restricted number of layers within a panel. This method seems to be the most accurate and adequate for CLT panels.

Other methods involve a combination of both empirical and analytical approaches based on model testing. No analytical approach has been universally accepted by CLT manufacturers and designers for now, and almost all of the studies have focused primarily on predicting stiffness and not strength properties of CLT panels in flexure. While flexural stiffness of CLT panels is usually of greater interest for designers than the strength, since the structural design is almost always governed by serviceability criteria, from a product standard development point of view there is a need to characterize the strength properties as well, to ensure certain minimum panel strength in service. There is a need to adopt a design methodology for determination of the stiffness and the strength properties of CLT in flexure by further exploring the shear analogy approach. It is expected that the proposed analytical approach will be accepted in the upcoming CLT product standard. The procedure to calculate the design properties should be based on material properties for lumber published in design standards, and should be consistent with the design philosophy in the CSA O86, the Canadian Standard for Engineering Design in Wood. Because of these potentially important features, the developed analytical methods will need to be comprehensively verified against test data.

Mechanical Properties of CLT Elements

Board Properties

Basic mechanical properties of the boards used in CLT elements vary from one producer to another. The most important European producer's use boards stress graded C24 according to EN Standards (EN 338 and EN 1912) or S10 according to DIN Standard. The equivalent in Canada would be MSR 1650Fb-1.5E lumber that gives a modulus of elasticity of about 10300 MPa.

Lumber Grade and Moisture Content

It is recommended to use boards having a maximum moisture content of 12% ± 2% for pilot.

Rolling Shear Modulus and Shear Deformation – Loads Perpendicular to the Plane

The rolling shear modulus depends on many factors such as species, cross-layer density, laminate thickness, moisture content, sawing pattern configurations (annual rings orientation), size and geometry of the board's cross- section, etc. The rolling shear modulus G_R is assumed to be 1/10 of the shear modulus parallel to the grain of boards, $G_{O.}$ Based on experience and the literature, the shear modulus G of wood products is generally assumed to be established between 1/10 to 1/20 of true modulus of elasticity i.e. $E_{True} / G_o \approx 12$ to 20.

Shear Deformation – Loads perpendicular to the plane

Lower ratios tend to be uneconomical and have higher influence of shear deformation, while larger ones may be controlled by the vibration properties and probably creep deformation. It is suggested that the shear deformation of CLT panels loaded uniformly may be neglected for elements having a span-to-depth ratio (l/d) minimum 30.

Duration of Load and Creep Behavior

Cross-laminated timber products are used as load-carrying slabs and wall elements in structural systems, thus load duration and creep behavior are critical characteristics that must be addressed in structural design. Time dependent behavior of structural wood products is addressed in design standards by load duration and service factors that adjust design properties.

Vibration Performance of Floors

Based on FPInnovations' test results, bare CLT floors were found to have mass varying from approximately 6 lb./ft.^{2}(30 kg/m^2) to 30 lb./ft.^{2}(150 kg/m^2), and a fundamental natural frequency above 9 Hz. Due to these special properties, the standard vibration controlled design methods for lightweight and heavy floors may not be applicable for CLT floors. Some CLT manufacturers have recommended that deflection under a uniformly distribution load (UDL) be used to control floor vibration problems. Using this approach, the success in avoiding excessive vibrations in CLT floors relies mostly on the designer's judgment. Besides, static deflection criteria can only be used as an indirect control method because they ignore the influence of mass characteristics of the floors. Therefore, a new design methodology is needed to determine the vibration controlled spans for CLT floors.

Code Provisions for CLT in U.S.A.

Cross laminated Timber classified as Type IV in the 2015 International Building Code (IBC) subject to the following standards.

Structural glued CLT shall be manufactured and identified in accordance with the American National Standards Institute ANSI/APA PRG 320-12, Standard for Performance-Rated Cross-Laminated Timber.

CLT shall be permitted within exterior wall assemblies with a 2-hour rating or less, provided the exterior surface of the CLT is protected by one of the following:

Fire-retardant-treated wood sheathing complying with Section 2303.2 and not less than 15/32 inch (12 mm) thick; Gypsum board not less than 1/2 inch (12.7 mm) thick; or A noncombustible material.

CLT floors shall not be less than 4 inches (102 mm) in thickness. It shall be continuous from support to support and mechanically fastened to one another. It shall be permitted to be connected to walls without a shrinkage gap providing swelling or shrinking is considered in the design. Corbelling of masonry walls under the floor shall be permitted to be used.

CLT roofs shall be not less than 3 inches (76 mm) nominal in thickness and shall be continuous from support to support and mechanically fastened to one another

CTL structures shall be considered a bearing wall system in the Seismic Design modifications to Table 12.2-1 of ASCE 7-10

CLT building systems shall comply with the drift and serviceability requirements of other lateral force resisting systems including ASCE 7-10 Table 12.12-1 and IBC Section 1604.3 criteria.

Future Scope

A plyscraper is a skyscraper made out of engineered lumber such as Cross Laminated Timber (CLT). With the right engineering, it's reported that plyscraper paneling can be as strong as concrete, with environmental benefits. The architect Michael Green has also drawn up plans for a 30-storey building.

Conclusion

CLT is an engineered timber product with approval of classification heavy construction timber Type IV in the 2015 International Building Code (IBC). CLT offers high strength and the structural simplicity needed for cost-effective buildings, as well as a lighter environmental footprint than concrete or steel. It also provides numerous other benefits, including quicker installation, reduced waste, improved thermal performance and design versatility. This paper briefly outlined various analytical design methods and properties of CLT panels adopted in Europe. The most common analytical approach is based on Mechanically Jointed Beam Theory (Gamma Method).

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