Bulletin of the *Transilvania* University of Brasov
Series II: Forestry • Wood Industry • Agricultural Food Engineering • Vol. 19(68) No. 1 – 2026
https://doi.org/10.31926/but.fwiafe.2026.19.68.1.5

# CROSS-LAMINATED TIMBER (CLT). A COMPREHENSIVE REVIEW

**Petrut FOLA**[1] **Alin OLARESCU**[1] **Aurel LUNGULEASA**[1]

***Abstract:*** *Cross-laminated timber (CLT) is one of the most advanced and innovative wood-based construction products of the latest decades. Research on this product is still ongoing, and various institutions, companies and scientists are making new contributions in this field. The present paper is part of the trend of finding new elements that will lead to the expansion of the market and the continued use of this product. The paper provides a synthesis of research in the CLT field, taking into account a series of aspects related to the working technique, wood species and materials often used, as well as its main physical and mechanical properties. Also, some standardisation elements and good practice guidelines are highlighted, without forgetting the assembly part with own joints or specific metal connectors. The main applications of CLT in the construction of multi-story houses based on wood are also emphasised, including floors and ceilings, side and intermediate walls and even in roofs. Furthermore, the paper discusses some elements of challenges and limitations, recent innovations and current trends, and especially elements of sustainability and life cycle assessment of the global circular economy. The final conclusion of the study is that this product is still in its early stages that coming years will benefit from the construction of light, ecological houses using wood materials such as the CLT structural composite.*

***Key words:*** *CLT, density, water absorption, physical properties, MOR, compressive strength, shear strength.*

## 1. Introduction

Cross-Laminated Timber (CLT) appeared in the 1990s as a result of efforts by the Swedish government and Austrian companies, institutes, and researchers to create a new wood-based composite product that would make use of by-products from the sawmilling industry. Cross-laminated timber has already been on the market for 20 years and it is the outcome of European research and industrial pioneer production in the field of laminated wood composites [6-9, 50]. Due to its versatility (being used for roofs, walls, and floor slabs between stories of buildings), it has already attracted global attention as a construction material [11]. CLT is an innovative, wood-based engineered material with recognised

---

[1] Faculty of Furniture Design and Wood Engineering, Transilvania University of Brasov, Universitatii Street no. 1, 500068 Brasov, Romania;
Correspondence: Aurel Lunguleasa; email: lunga@unitbv.ro.

performance compared to traditional building materials. It competes in the construction sector with brick, concrete, glass, and steel, but also with wood frame construction, offering clear advantages in terms of weight, environmental and structural performance, sustainability, earthquake resistance, speed and ease of construction, and preserving the aesthetic qualities of wood [12-16, 24-30, 36-46]. Bayramoglu et al. [6] showed that the main advantages of CLT are low carbon emissions, short construction time, high structural performance, very good seismic behaviour, and sustainability. However, the main barrier to its sustained future development remains the high cost of high-quality graded timber (with construction costs using CLT observed to be 4.43% higher than those of concrete-based houses). CLT represents a much more versatile way of using timber and obtaining sustainable construction solutions [11, 13] allowing for tall buildings of around over 18+1 since 2017 as UBC dormitory in Vancouver stories [47, 48, 51, 53-55], even though it has the disadvantage that vibrations and noise between floors can be felt, creating a certain discomfort among residents.

The CLT composite is characterised by the fact that the panel has an odd number of graded wooden lamellae layers, arranged cross to each other, in order to obtain good strength in all directions of the panel and high dimensional stability. For construction safety, this composite is a structural one; the sawn softwood used must be of the highest quality, free of defects that could affect its strength, and the adhesives must be structural (with high bonding power like MUF, PF, pMDI, PUR etc.), thus ensuring increased strength and solidity for the wooden construction. The 3, 5, or 7 lamellae (rarely 9) are glued together with structural adhesive (the face layers being the main ones, and the core layers the secondary ones). Since not every layer necessarily requires edge-gluing of the long elements (which were initially finger-jointed), even gaps of up to 3 mm between these lamellae are acceptable from strength point of view but not easy to accept by final users (Figure 1). Regarding its relationship with the environment, Gezer et al. [28] stated that this composite is wood-based, which has the ability to store carbon, is renewable, reusable, recyclable, has a low carbon impact, is environmentally friendly, and promotes good health for the residents of the respective house.

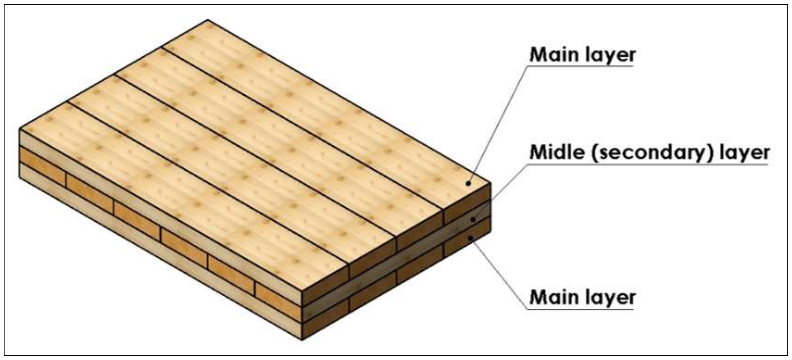

Fig. 1. *Arrangement of the layers in a three-layer Cross-Laminated Timber (CLT) panel*

The CLT composite product is experiencing accelerated global development. Current worldwide production of CLT exceeds 3 million $m^3$, with exponential growth from year to year [28]. At present, 80% of production is concentrated in Austria, Germany (17%), and Switzerland (3%). Research in the CLT field is also advancing rapidly; in this regard, Buck et al. [12] and Bülbül et al. [13] have developed several types of CLT using different wood species and adhesives. According to studies in the German speaking DACH region, passive houses made with CLT and well insulated have been available since 2010, and the amount of energy consumed for heating buildings in cold regions is lower when CLT-type wood composites are used.

CLT is recognised as a robust solution for multi-story buildings in seismic areas due to its lightweight construction, the natural elasticity of wood, and the presence of multiple and simple connections which were developed especially for them [51]. The same authors state that CLT is a versatile product, able to continuously adapt its technology and construction details through new joints or innovative connectors that better withstand seismic activity (especially vertical plane vibrations). Flores et al. [25] stated that CLT is recommended in seismic regions, in areas with strong winds, and in wildfire-prone zones. CLT was used as prefabricated flooring and wall panels in the 18-story student residence at the University of British Columbia in Canada [53].

De Araujo et al. [15] developed a synthesis study on CLT, addressing whether it should be considered a prefabricated panel, a construction element, or a timber structure. They also studied the functions, characteristics, performance, and applications of this wood-based structural composite. Regardless of the type of article (generalist, intermediate or specific), the period with the highest number of CLT-related publications was 2018-2022, with a peak in 2021, which corresponds to the rapid increase of production capacities in Central Europe for the first two categories and 2019 for the third. CLT is considered a structural composite, used in construction as a semi-finished element. From a linguistic perspective, correct terms include CLT element and CLT panel, while CLT system and CTL building system are considered incorrect.

The present research aimed to conduct a detailed analysis of the works related to the CLT composite, in order to report on the current state of research, the design and construction difficulties, and future opportunities and challenges.

## 2. Materials and Methods

### 2.1. Wooden Species

CLT can accommodate almost any wood species that is both lightweight and resistant; however, softwood species are predominantly used. De Araujo et al. [15] synthesised that the following coniferous species are commonly employed: Norway spruce (*Picea abies* L. (H. Karts.)), White fir/Silver fir (*Abies alba* Mill.), Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.), Swiss pine (*Pinus cembra* L.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Bull pine (*Pinus taeda* Carl Linnaeus), as well as a hardwood species, Rose gum (*Eucalyptus grandis* W. Hill).

Buck and Hagman [11] and Buck et al. [12] used European Norway spruce in their research, with five layers of lamellae in the

CLT panel. The lumber quality class was Q61, in accordance with European Standard EN 14081:2011 [17], corresponding to the C24 grading class in EN 338:2009 [21]. The average density of the lumber was 462 kg/m³, determined through the gravimetric method of drying and weighing specimens (ISO 3131:1975 [33]). After planning, the lamellae dimensions were 19 × 94 mm, without finger-jointing along the length.

Bülbül et al. [13] provided an overview of species currently used in CLT construction, noting that spruce, pine, and fir are widely employed in Europe and Canada; Douglas fir, spruce, and larch are common in the USA; while pine is predominantly used in Australia and New Zealand, where less than 5% of CLT is produced. A study conducted in Italy investigated the use of regional resources, such as poplar and chestnut (*Castanea sativa* Mill.), for CLT production where high load-bearing capacity was not required. Other authors used poplar (*Populus alba* L.) with a density of 400 kg/m³, but emphasised that although it is a fast-growing species (i.e. Paulownia hybrids from Europe), its low-density results in inferior performance compared to pine-based CLT, requiring densification. Gezer et al. [28] employed spruce and alder timber, both separately and in combination.

Regarding the dimensions of CLT panels, in the study of De Araujo et al. [15] was reported that overall thickness can reach up to 500 mm, although typical thicknesses are 60, 100, and 140 mm, with standard widths of 600, 1,200, 2,400, and 3,000 mm, and usual lengths of 5 m.

Bülbül et al. [13] produced a five-layer CLT panel using lumber from Scots pine (*Pinus sylvestris* L.), Turkish fir (*Abies bornmuelleriana* Mattf.), and sessile oak (*Quercus petraea* Carolus Linnaeus), with the outer layers made exclusively of pine and oak. Since the raw material strongly influences the properties of CLT, the main physical and mechanical properties were reported in the study.

Other authors [12,13] developed a five-layer CLT composite with diagonal layers using local hardwood species such as black locust (*Robinia pseudoacacia* L.) for the parallel layers and eastern white pine (*Pinus strobus* L.) for the two diagonal layers. Although the classical CLT structure involves the perpendicular arrangement of five adjacent layers at 90°, Buck et al. [12] advanced research by investigating an alternative arrangement with intermediate lamellae set at 45°. Specifically, the configuration consisted of: the top layer longitudinally, the second layer at 45° to the right, the third layer longitudinally, the fourth layer at 45° to the left, and the final layer longitudinally (same as the first), thus creating a symmetrical structure. The wood species used was Norway spruce (*Picea abies* L. (H. Karst.)).

Korean research conducted by Choi et al. [14] employed an indigenous species, Korean larch (*Larix kaempferi* (Lamb.) Carr.), which is well known and widely used in CLT applications in Korea, even if less than 1% of the world. The same study noted that spruce-fir, hem-fir, Douglas fir, and yellow pine (*Pinus ponderosa* C. Lawson) are commonly used in Europe and North America, while larch and Hinoki cypress (*Chamaecyparis obtuse* (Siebold & Zucc.) Endl.) are preferred in Japan. Furthermore, the study demonstrated that combining timber layers with plywood layers can improve the strength and other mechanical properties of CLT composites, but this is maybe the next generation.

Gezer et al. [28] investigated the optimal

CLT structure (with maximum mechanical properties) as a function of timber strength class. The study identified three main softwood species used in CLT: spruce, pine, and fir. In addition, fast-growing hardwood species such as poplar, eucalyptus, magnolia (*Magnolia grandiflora* L.), and bamboo (*Dendrocalamus giganteus* Munro) were noted as alternatives.

The selection of lumber for CLT is crucial; the European Standard EN 338:2016 [20] classifies conifer wood into 12 strength classes by machine grading (C14, C16, C18, C20, C22, C24, C27, C30, C35, C40, C45, and C50), and deciduous wood into eight classes (D18, D24, D30, D35, D40, D50, D60, and D70). Since higher-quality classes are more expensive and not easy to get, large manufacturers generally use class C24, and less frequently C18, C16, C14, or C30.

Pang et al. [44] conducted an experiment using a five-layer CLT panel with a thickness of 150 mm, a width of 1 m, and a length of 4.2 m, made from larch (*Larix kaempferi* (Lamb.) Carr.) and red pine (*Pinus densiflora* Siebold Zucc.). The lamella thickness was 30 mm, and three types of joints were used: spline joints, butt joints, and half-lap joints. The lumber grading classes were C12-C8-C6, with densities of 587 kg/m³ for larch and 476 kg/m³ for pine.

Bayramoglu et al. [6] used two standards for sorting lumber intended for structural use in CLT construction: the European Standard EN 338:2016 [20] and the Turkish Standard TS 1265:2012 [52]. The Turkish standard is based on visual grading of lumber (knots, grain deviation, cracks, and abnormal discolorations). It is considered that visual grading (three classes: Grade 1, 2, and 3) is more widely applied in industry due to its simplicity and lower costs.

In their study conducted in Turkey, Bayramoglu et al. [6] selected two softwood species most frequently used in the industry, namely Oriental spruce (*Picea orientalis* (L.) Link) and Scots pine (*Pinus sylvestris* L.). They applied the three quality classes of lumber defined by TS 1265:2012 [52] at 12% moisture content, using two lamella dimensions: 120 × 10 × 2.5 cm and 240 × 10 × 2.5 cm.

## 2.2. CLT Building Structures, Connections, and Joints

As a structural composite, CLT panels may consist of 3, 5, 7 or 9 bonded layers; however, an even number of layers is not permitted, as it would disrupt the structural symmetry of the composite. Furthermore, the presence of adjacent layers arranged perpendicularly provides this product with high and superior strength in the main direction, which promotes its use in construction for walls, ceilings, and floor slabs. In a building, CLT panels can be joined together using various specific connections [44]. Other research [11-16, 24] has focused on the entire wall structure, which includes the inner layer of fibre cement, thermal insulation, the CLT panel with two outer plywood layers, and the exterior layer of cement-based plaster (Figure 2).

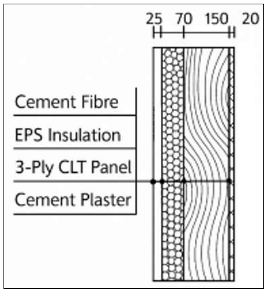

Fig. 2. *Wall with a CLT panel used in construction*

Other authors [13-16, 24-30, 37-41] found that a combination of CLT (as a structural and load-bearing element) and glass in the façade of a building is energy-efficient and provides high thermal performance.

## 2.3. Manufacturing Process

The manufacturing process of CLT begins with timber pieces and the end products is a layered composite. The main operations applied to the machine graded sawn wood include ripping and cross-cutting, defect removal, finger-jointing of lamellae along their length, and planning of the boards. Afterward, the layers are assembled, adhesive is applied between them, and the main pressing operation follows, which can be either cold or hot pressing using high frequency. Compared to other pressing processes, CLT production requires both vertical pressing (to bond the layers together) and side pressing (in both directions, to bond the lamellae edge to edge within each layer). After the adhesive cures during the pressing step and the product stabilises, it undergoes finishing operations (Figure 3).

In the study by Buck et al. [12], CLT panel pressing was carried out in a single step using a hot mono-level press. In a later study, Buck and Hagman [11] used a pressure of 0.37 MPa, and Korean research by Choi et al. [9] applied hot pressing at 140°C for 3 minutes at 0.1 MPa, while cold pressing was performed for 6 hours at 0.1 MPa [9].

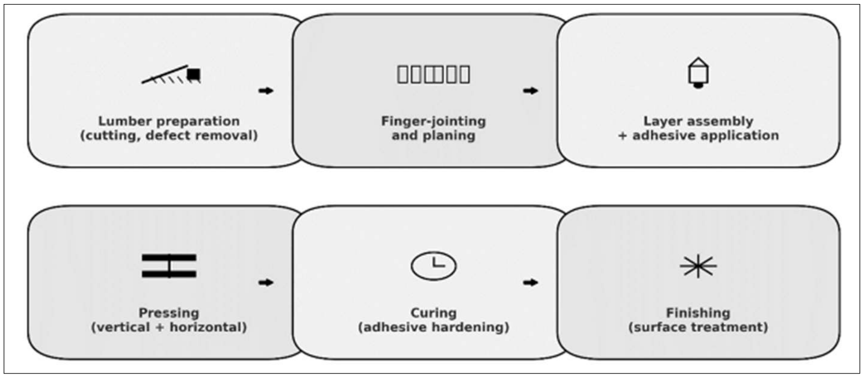

Fig. 3. *CLT manufacturing flow*

The CLT manufacturing process described by Zhang et al. [56] used lumber with a density of 450 kg/m³, dried to 9.4% moisture content. A single-layer polyurethane resin was applied between layers at a spread rate of 200 g/m². Cold pressing was performed for 8-12 hours at a temperature of 15°C. The resulting CLT panel had dimensions of 1,100 × 1,100 × 48 mm. Gezer et al. [28] employed cold pressing with a pressure of 0.8 N/mm² for spruce and 1.2 N/mm² for alder, along with a lateral pressure of 0.2-0.5 N/mm².

Bayramoglu et al. [6] reported the use of polyurethane adhesive at a spread rate of 160 g/m², with an industrial hydraulic press capable of simultaneously applying a vertical pressure of 0.8 N/mm² and ahorizontal pressure of 0.3-0.5 N/mm². The resulting CLT panels had dimensions of 2,400 × 1,200 × 75 mm.

### 2.4. Adhesives and Bonding Technologies

In general, CLT technology employs high-strength structural adhesives, since this composite is used in construction, where materials with high mechanical performance are required. The research by Bülbül et al. [13] shows that in order to achieve significant mechanical strength of CLT, adhesives based on formaldehyde are commonly used (MUF), such as those containing melamine, resorcinol, and phenol resins. For load-bearing beams, stronger adhesives are required, such as phenol-resorcinol formaldehyde, polyurethane (PUR), and melamine-urea formaldehyde (MUF). Moreover, polyurethane adhesive (PUR), which is solvent- and formaldehyde-free, is the most widely used and in demand (EN 301: 2006 [10]).

Five-layer panels produced by Buck et al. [12] were bonded with melamine-urea-formaldehyde (MUF) adhesives with a hardener, applied by roller spreading, except for the edges of the intermediate panels, which were not glued. The adhesive-to-hardener ratio was 39%, and the specific adhesive consumption was 320 g/m², almost double that used in the furniture industry. Buck and Hagman [11] continued their previous research [12] on using lamellae inclined at 45° in the longitudinal direction, this time focusing on compression strength, employing the same adhesives as in the earlier study.

Gezer et al. [28] reported a specific consumption of 160 g/m² of polyurethane adhesive in the solution. Choi et al. [14] used phenol-formaldehyde (PF) adhesive (with calcium carbonate as a 5% hardener and coconut shell flour as filler, at a specific consumption of 140 g/m²) for the outer plywood layer of the composite, and resorcinol-phenol-formaldehyde adhesive for the inner lamellae layer. Bülbül et al. [13] tested two types of adhesives, polyvinyl acetate (PVA) and polyurethane (PUR), with a specific consumption of 100-130 g/m². Tian et al. [51] used polyurethane adhesive, applied only on one face of the lamellae, at a specific consumption of 220 g/m² and pressed at 1.2 MPa for 2 hours.

### 2.5. Mechanical Properties

The bending strength of CLT panels can be determined on any universal composite materials testing machine, which provides a force of about 10 tons, in three or four points (two for supporting and one or two for pressing). Figure 4 shows the diagram of the determination of the modulus of rupture (MOR) and the modulus of elasticity (MOE), when the determination is made in four points. It is observed that, usually, the arrangement of the two bending force application punches separates the distance between the supports into three equal parts, each having a size of six times the thickness of the CLT specimens (Figure 4).

The shear strength of CLT by compression uses three specimens (Figure 5) with flat dimensions of 100x50 mm, which are glued together offset, so that there are two shear surfaces of 50 x 50 mm each.

Rolling shear is a new type of CLT shear test, which involves an angle of application (Figure 6) of the force in the longitudinal direction of the three glued specimens. The resistance to this type of shear is determined as the ratio of the maximum breaking force to the shear area through the two surfaces, taking into account the angle of the force application (Figure 6).

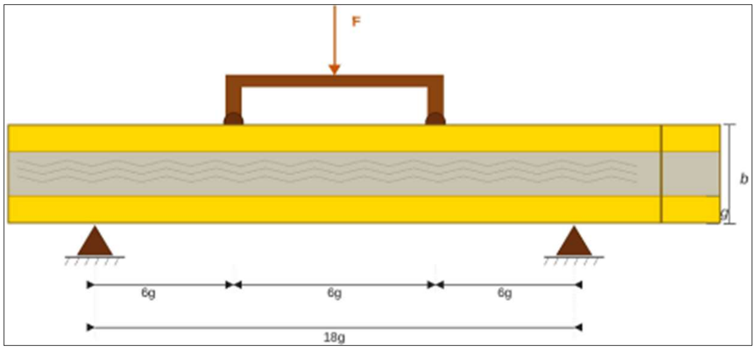

Fig. 4. *MOR and MOE for static bending, when the test is applied in four points*

Some authors investigated the influencing factors on the rolling shear performance of CLT panels manufactured in Australia. The study employed three pine species native to Australia: southern pine, radiata pine, and hoop pine. The primary factor examined was the equilibrium moisture content of the wood, while the modulus of elasticity (MOE) and the presence of knots were also considered.

The specimens tested had the following dimensions: cross-section 135 × 30 mm and length 56.6 mm. The relationship for rolling shear depended on force of rupture and dimensions (Equation 1).

$$f_r = \frac{F_{max} \cdot cos\alpha}{L \cdot w} \qquad (1)$$

where:

$f_r$ is the resistance [N/mm$^2$];

$F_{max}$ – the maximum force [N];

$L$ – the length of shear [mm];

$w$ – the width of shear zone [N].

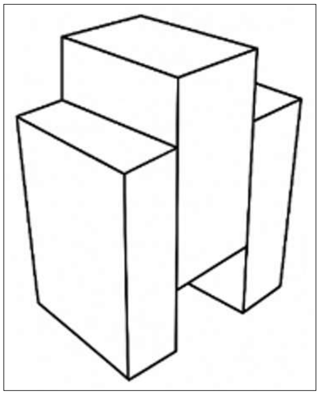

Fig. 5. *The CLT specimens used for shear testing under compression*

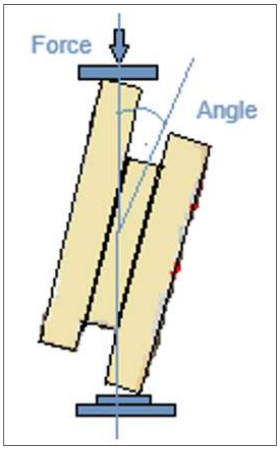

Fig. 6. *Rolling shear of the CLT*

## 3. Results

### 3.1. Environmental Impact, Life-Cycle Assessment, and Circular Economy

Environmental performance is based on the fact that wood is much more environmentally friendly than concrete, steel, or plastic, thus reducing carbon emissions. CLT also sequesters carbon dioxide for an extended period, while its recyclability at the end of life is also considered. Studies conducted in Canada have shown that CLT emits VOCs and free formaldehyde within the limits of the international standards regulating these aspects [24].

De Araujo et al. [15] classified construction materials into three categories:

- *High carbon content:* window glass (99 kg $CO_2$ eq/kg), window frame plastics (8.7), polyethylene membrane (2.7), steel (2.2 kg $CO_2$/kg);
- *Low carbon content:* ceramic tiles (0.87), mineral wool (1.07), gypsum plasterboard (0.39), CLT and GLT (0.31), OSB (0.29), concrete C30 (0.18), clay plaster (0.09);
- *Negative carbon content:* GLT bamboo (-0.15), hemp fibre (-0.44), reed mat (-0.46), straw (-0.60 kg $CO_2$ eq/kg).

Its structural performance is accompanied by a low environmental impact. Keeping a low carbon footprint is crucial for ensuring the product's future sustainability [11, 12]. In a latter study, as well as in others [29], comparisons were made between annual carbon emissions: for example, a six-story CLT building emits 724 t of $CO_2$, whereas a comparable concrete building emits 1,984 t, i.e., 2.7 times more.

The increase in heating demand for buildings in cold regions of China leads to higher fossil fuel consumption and consequently higher greenhouse gas (GHG) emissions. Energy consumption in the construction sector is very high, around 46% in France and 41% in the USA. Beyond being renewable and sustainable, wood-based products such as CLT generate lower pollution by absorbing and sequestering $CO_2$ and by having a reduced environmental impact in life cycle assessment (Figure 7).

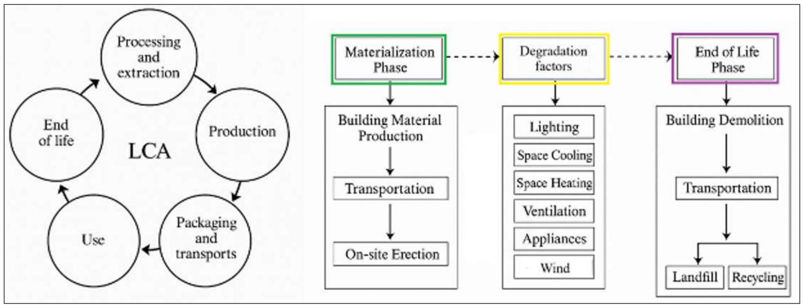

Fig. 7. *Life-Cycle Assessment (LCA) of CLT*

In relation to the interaction of CLT with the environment, adhesives must also be considered. Zhang et al. [56] pointed out that most synthetic adhesives are environmentally unfriendly and compromise the durability of structures, while the large amounts of adhesives used cause environmental pollution [41].

Iezzi et al. [30] stated that the life cycle assessment (LCA) of a building must be correlated with the International Organization for Standardization ISO 14040:2006 [31] and the European Standard EN 15978:2026 [18]. LCA consists of five phases (Figure 7) and depends on the type of material, the long-term performance of the building – especially after seismic events – and the recyclability of the construction materials used. They analysed the influence of major earthquakes on the service life of buildings and proposed technological solutions to improve building performance. Two main conclusions emerged: the cost of CLT buildings is influenced by the structural schemes of the composite and the type of connectors used, and construction costs may be reduced if these factors are considered during design, by recovering and reusing materials from earthquake-damaged buildings.

Sandoli et al. [48] highlighted that CLT-based structures have great potential to reduce $CO_2$ emissions: emissions of wood-based structures are about 250 kg/m², compared to 850 kg/m² for concrete structures and 450 kg/m² for light steel structures per built area.

Some authors analysed the environmental impact of CLT manufactured in Japan through an input–output assessment, aiming to evaluate greenhouse gas (GHG) emissions throughout the CLT manufacturing process. It was demonstrated that the manufacturing of CLT emits significantly less than cement and steel production used in construction. Among industrial sectors, construction accounts for 38% of total $CO_2$ emissions. The purpose was to assess energy consumption and GHG emissions within CLT manufacturing. Cement and electricity production (indirect activities in CLT production) were identified as the least environmentally friendly contributors. For CLT, the total GHG emissions were estimated at 521 kg $CO_2$ eq/m³ (including direct and indirect emissions). If only direct emissions were considered, the average was 166 kg $CO_2$ eq/m³.

Recently, increasing attention has been paid to the fate of finished products after end-of-life or decommissioning. It is increasingly required that recyclability, refurbishment, and reuse be already considered at the design stage. CLT is highly suitable for recycling since it consists predominantly of wood.

Moritani et al. [41] showed that construction systems using metal connectors, screws, and bolts have higher potential for deconstruction, reuse, or recycling. It is assumed that wood has a reduced carbon footprint compared to other building materials. CLT is more advantageous than wood–concrete or reinforced-concrete systems. CLT may also be substituted by laminated veneer lumber (LVL) or glulam, but the design flexibility of metal connector’s remains a significant advantage.

### 3.2. Physical-Mechanical, Acoustic, and Thermal Properties of CLT

The mechanical performance of cross-laminated timber (CLT) is one of the key factors driving its adoption as a structural material. Due to its crosswise arrangement of lamellae, CLT panels provide strength and stiffness in both principal directions, distinguishing them from other engineered wood products such as glued laminated timber (GLT), which is optimised for one-directional load-bearing.

Bending properties are of particular

interest in research. Buck and Hagman [11] reported that CLT panels with lamellae arranged at 45° demonstrated up to 35% higher bending strength compared to conventional 90° arrangements, highlighting opportunities for optimisation through non-traditional layups. Further experiments on compression performance revealed improved stiffness values in densified or modified lamella configurations [12,13].

Fire performance is another critical mechanical aspect. While wood is easily combustible, CLT exhibits predictable charring behaviour (0.7 mm/min for spruce), which slows the rate of fire penetration.

Perković et al. [46] modelled fire resistance in Croatian CLT panels and demonstrated that protective layers such as gypsum board significantly increase fire resistance by delaying ignition.

Acoustic performance remains a challenge for CLT. Studies indicate that bare CLT floors transmit impact and airborne noise, especially at low frequencies, which may cause discomfort in multi-story buildings. They showed that acoustic insulation can be improved by incorporating additional layers such as elastic underlays, mineral wool, or gypsum boards, achieving reductions of 22-32 dB.

In seismic applications, CLT has shown excellent potential due to its lightweight nature and ductile connections. Sandoli et al. [48] found that in most strong-earthquake simulations, failures occurred primarily in metal connectors rather than in the CLT panels themselves, underlining the importance of connection detailing. Similarly, Iezzi et al. [30] emphasised that connector design significantly influences the seismic resilience and lifecycle costs of CLT buildings.

Overall, research consistently demonstrates that while CLT has favourable structural and environmental performance, its broader application requires continued improvements in acoustic insulation, fire resistance, and connection systems, alongside optimisation of lamella configurations for enhanced strength and stiffness.

CLT is considered a construction system used for floors, walls, and roofs, with high load-bearing capacity between supports, similar to GLT (Glue-Laminated Timber), although the latter applies only to beams. CLT also demonstrates high fire resistance and seismic performance equivalent to a magnitude 7.2 earthquake on the Richter scale. They analysed the influence of drying methods (ambient and fan kiln drying) on CLT panels partially or fully immersed in water, using *Pinus radiata* (D. Don). Starting from dry panels, moisture content increased to 45% after 24 hours of immersion.

Considering that static bending strength (four-point bending, according to EN 408:2010 [22]) is the most important mechanical property of CLT, Buck et al. [12] compared the arrangement of lamellae layers at 45° versus 90°. For each type, 10 specimens with dimensions of 95 × 590 × 1200 mm were tested. The experiments showed that panels with a 45° arrangement had 35% higher bending strength compared to normally arranged panels at 90°. The conclusion was that new CLT panel structures can achieve higher load-bearing capacity while using less material. The specimens were tested only in the major direction.

A later study by Buck and Hagman [11] considered uniaxial compressive strength. The specimens had cross-sections of 95 × 180 mm and a height of 570 mm, corresponding to six times the specimen thickness. Stiffness under compression was determined by calculating the modulus of elasticity, considering the force at 10 and 40% of the maximum load and the corresponding deformation. Compressive strength values were 30 and 26 N/mm², while stiffness values were 5500 and 7100 N/mm², representing increases of 30 and 15%, respectively.

The average modulus of rupture (MOR) was 35 N/mm² and the modulus of elasticity (MOE) was 9300 N/mm² for the conventional (90°) layer arrangement, while for the 45° arrangement, the values were 52 N/mm² and 10,900 N/mm², respectively. Only three dominant failure modes were observed, the main one being by shearing.

Choi et al. [14] aimed to increase CLT strength by introducing inner plywood layers. The composite was tested on a universal testing machine in four-point bending, with a support span equal to 48 times the specimen thickness; plywood was tested in three-point bending with a span of 24 times the thickness and a loading rate of 10 mm/min. Compressive strength was measured at a crosshead speed of 5 mm/min, and tensile strength at 2 mm/min. It was observed that increasing the number of plywood layers reduced the MOR: 67 MPa for the composite with three plywood layers and 44 MPa for the composite with five plywood layers. The MOR of individual plywood (85 MPa) exceeded that of the composite, whereas individual CLT (MOR = 99 MPa) was higher, indicating that structural non-uniformity in the composite decreases its mechanical properties. The study concluded that increasing veneer thickness (rather than the number of layers) is recommended for plywood layers.

The relationship for bending stiffness, according to ASTM D198:2022 [3], are presented in Equations (2) and (3).

$$MOR = \frac{3}{2} \cdot \frac{F_{max} \cdot l}{b \cdot t^2} \tag{2}$$

$$MOE = \frac{23}{108} \cdot \frac{l^3 \cdot (P_2 - P_1)}{b \cdot t^3 \cdot (a_2 - a_1)} \tag{3}$$

where:

*MOR* is the Modulus of Rupture [N/mm$^2$];
$F_{max}$ – the maximum force [N];
$l$ – the length of sample [mm];
$b$ – the width of sample [mm];
$t$ – the thickness of sample [mm];
*MOE* – the Modulus of Elasticity [N/mm$^2$];
$P_1$ – the force of 10% from maximum force [N];
$P_2$ – the force of 40% from maximum force [N];
$a_1$ – the deformation for $P_1$ [mm];
$a_2$ – the deformation for $P_2$ [mm].

Zhang et al. [56] stated that CLT exhibits good fire performance and excellent mechanical properties. CLT wall panels with openings for doors and windows showed much better properties than assemblies made by joining cut panel pieces (ASTM E564-06:2018 [5]). Young et al. [55] evaluated the bending strength of CLT panels joined with mechanical fasteners-threaded nails, polished nails, and screws – in place of adhesives that may present durability issues over time. Multiple nail types, insertion angles, numbers of fasteners, and placement positions were investigated.

De Araujo et al. [15] synthesised the following typical CLT properties: density 480-500 kg/m³; compressive strength 21-24 N/mm²; MOE 11-26 GPa; thermal conductivity 0.12 W/m·K.

Reported fire reaction ratings included: reaction-to-fire class D (medium), smoke class s2 (average), droplet class d0 (no flaming droplets), and char rate 0.6-0.9 mm/min (or equivalently 0.6-0.9).

### 3.3. Legislation, Standardisation, and Best Practice Guidelines

De Araujo et al. [15] highlighted that the main standards focusing on CLT are: ISO 16696-1:2019 worldwide [32], EN 16351:2021 in Europe [19], ANSI/APA PRG 320:2025 in North America [2], SANS 8892:2020 in South Africa [49], JAS 3079:2019 in Japan [35], and ABNT NBR 7190:2022 (part 7) in Brazil [1]. Using the American standard ASTM E564:2018 [5], the shear performance of CLT was determined.

Moritani et al. [41] analysed the possibility of reinforcing CLT with metal in hybrid structures to improve performance. The main improvement is the enhanced ratio between mechanical properties and self-weight, while maintaining a reduced environmental impact.

Gezer et al. [28] applied EN 408:2010 [23] and other standards [3-5, 34, 56] to determine the modulus of rupture and the modulus of elasticity in static bending. For evaluating the lumber used in CLT construction, EN 338:2016 [20] was employed alongside a non-destructive acoustic testing device. Regarding static bending strength, the optimal timber grading structures were C24-C27-C24 for spruce CLT and D18-D24-D18 for alder CLT, while for mixed-species CLT they were C30-D40-C30 and D18-C30-D18. With respect to the modulus of elasticity in static bending, the optimal grading structures differed: C22-C27-C22 for spruce, D35-D30-D35 for alder, and C16-D24-C16 and D24-C24-D24 for mixed-species structures. Structural symmetry was identified in all cases.

Pang et al. [44] conducted a study on the sound insulation capacity [3, 5, 34], using a rubber ball as the impact source, and the vibration performance of CLT floors, depending on the wood species and the connections (joints) between panels. It was found that the type of CLT joint did not significantly influence either the vibrations or the sound insulation capacity of CLT.

Bayramoglu et al. [6] analysed the influence of wood species and lumber strength class on the physical-mechanical properties and the production cost of CLT. The TS EN 408:2010 [22] standard was applied for static bending, shear parallel to the grain, and compressive strength. The specimen dimensions were 1,080 × 108 × 54 mm for bending tests, and 324 × 108 × 54 mm for compression parallel to the grain. For the group of spruce specimens, a density of 454 kg/m$^3$, bending strength of 19 N/mm$^2$, MOE of 10,750 N/mm$^2$, shear strength of 2.4 N/mm$^2$, and compression strength of 45 N/mm$^2$ were obtained, and for the group of Scots pine specimens, a density of 542 kg/m$^3$, bending strength of 25.4 N/mm$^2$, MOE of 12,200 N/mm$^2$, shear strength of 2.9 N/mm$^2$, and compression strength of 55 N/mm$^2$ were obtained.

Once again, the results confirm that Scots pine outperforms spruce in both mechanical properties. For composite CLT with a density of 500 kg/m$^3$, a thermal conductivity of 0.13 W/m·K, specific heat of 1,500 J/kg·K, and a thermal resistance of 1.1538 m$^2$k/W were found. The thermophysical properties and layer configuration of a cross-laminated timber (CLT) external wall system designed for climatic conditions in Beijing were evaluated. The wall assembly consisted of four distinct layers: cement fibre board, expanded polystyrene (EPS) insulation, CLT panel, and cement plaster. The outermost layer was a cement fibre board with a thickness of 20 mm, characterised by a relatively low thermal conductivity (0.082 W/m·K) and moderate density (350 kg/m³), contributing to both protection and thermal resistance. This was followed by a 50 mm EPS insulation layer, which exhibited a very low thermal conductivity (0.035 W/m·K) and low density (25 kg/m³), making it the primary thermal insulating component of the assembly. Consequently, this layer provided the highest thermal resistance (1.4286 m²K/W) among all layers. Overall, the thermal resistance of the wall assembly was dominated by the insulation layer, while the CLT panel contributed significantly to thermal inertia. This combination reflects a design strategy that balances insulation performance with structural efficiency and thermal mass.

Tian et al. [51] investigated the predictability of the compressive strength of cross-laminated timber (CLT) in the major (in-plane) direction based on the density and compressive strength of larch laminations. The authors developed a predictive model describing this relationship. The results indicated that when the densities of the CLT and the lamina were approximately equal, the in-plane compressive strength of larch CLT reached approximately 72% of the compressive strength of the individual lamina. Furthermore, when the lamina density was considered as a predictor, the in-plane compressive strength of CLT was found to correspond to approximately 74 times the density, as determined using Monte Carlo simulation. A linear relationship was found between density and compressive strength.

Flores et al. [25] examined the static three-point bending strength of CLT under impulse loading conditions. It was reported that various span-to-depth ratios may be employed, such as: L/h=14L/h = 14L/h=14 [30], L/h=15L/h = 15L/h=15, or L/h=18L/h = 18L/h=18; however, a lower ratio of 6-7 was adopted in the study. All CLT specimens exhibited failure governed by shear in the cross-section.

They performed a validation of the physico-mechanical properties of cross-laminated timber (CLT) manufactured from *Eucalyptus benthamii* (Maiden & Cambage), a fast-growing species cultivated in Brazil (approximately 23 years old), using the Finite Element Method (FEM). The study evaluated density as well as key mechanical properties, including static bending strength, compression parallel to the grain, and shear strength. The results showed no significant differences between the experimentally measured values and those predicted by the finite element model, confirming the reliability of the numerical approach.

Gašparík et al. [27], investigated the bonding performance of cross-laminated timber (CLT) manufactured from three common wood species – silver birch (*Betula pendula* Roth), European aspen (*Populus tremula* L.), and Norway spruce (*Picea abies* (L.) H. Karst.) – using a one-component polyurethane adhesive.

The results showed that CLT panels made from spruce exhibited an average bond shear strength of 1.9 N/mm², whereas significantly higher values were obtained for hardwood-based CLT. Aspen CLT reached a bond shear strength of 3.3 N/mm², while birch CLT achieved up to 3.9 N/mm². The aspen and birch CLTs met the minimum criterion for bond shear strength of 1 N/mm² specified by EN 16351:2021 [19]. The bond shear strength values were

73.7% higher for aspen and 105.3% higher for birch compared to spruce CLT.

The fire resistance of CLT was investigated by Perković et al. [46] using analytical modelling methods applied to CLT panels manufactured in Croatia, with both protected and unprotected categories. Three working variables were considered: charring rate, heat release, and smoke generation. The study observed that although CLT is more flammable than concrete or brick, the formation of a char layer on the surface during burning slows down the combustion process. It was concluded that adding a protective board, such as gypsum, delayed the risk of CLT ignition. The temperature of the gaseous phase is a critical parameter that influences many aspects of fire compartments.

### 3.4. Challenges and Opportunities of CLT

Regarding the CLT product, the following challenges were identified:

- to have higher mechanical resistance;
- to solve acoustic problems, especially in multi-floor houses;
- to find methods of using lower quality (B and C) and undersized timber (under 1.5 m);
- to gradually eliminate joints with metal connectors and screws, implementing other joint solutions specific to these products;
- to simplify the manufacturing flow by finding mechanised installations and lines specific to these products.

From the point of view of opportunities, the following elements were found:

- the use of indigenous wood resources for each country or region;
- the location of CLT production units next to large sawmills, or next to Glulam/SWP factories (to benefit from experience in the field of making laminated products) (Figure 8).

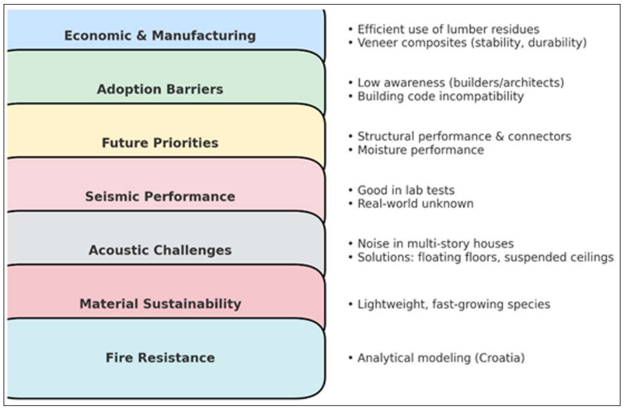

Fig. 8. *The main challenges and opportunities of CLT products*

### 4. Discussions

The species used in CLT structures are of all types, with softwoods such as Norway spruce prevailing, and less often hardwoods [15]. There was also a tendency to use regional species, easier to acquire for the authors of the research, such as Douglas fir and larch [13]. Some authors like Geser et al. [28] also combined softwood species with hardwoods.

The density of CLT depended directly on the density of the species used, with a very slight increase due to the dry adhesive and the pressure used. The static bending strength depended greatly on the density of the composite. Thus, Pang et al. [44] found a density of 476 kg/m$^3$ using larch wood and a MOR resistance of 35 N/mm$^2$, while Bayramoglu et al. [6] a density of 450 Kg/m$^3$ and a MOR resistance of 22 N/mm$^2$.

Regarding the adhesion of the surfaces of the lamellae in the CLT composition, all norms requested that a structural adhesive must be used, which ensures a high resistance to the high composite.

In this sense, Bayraboglu et al. [6] used hot PUR, with a specific consumption of 160 g/m$^2$ and a specific pressure between layers of only 0.8 MPa. Zang et al. [56] used cold gluing for 8-10 hours, with a consumption of 200 g/m$^2$ and a high pressure of 20 MPa. Other authors [11, 14, 28] used MUF and resorcinol formaldehyde at a consumption of 320 g/m$^2$, formaldehyde phenol at a specific consumption of 140 g/m$^2$, and Tian et al. [51] used cold polyurethane adhesive at a specific pressure of 1.2 MPa, a consumption of 220 g/m$^2$, and a total curing time of 30 days. It was observed that in the case of using cold adhesives, the pressure was slightly increased (1.2 N/mm$^2$), but it did not reach the pressure used for other composites, such as plywood, with over 3 N/mm$^2$.

## 5. Conclusions

The following main conclusions were drawn from the comprehensive analysis carried out in this work:

- The paper synthesises the most widely read works in the field of CLT, finding that this product has a number of advantages;
- CLT is a laminated product that maintains the rules of solid wood panels (SWP) structure, namely an odd number of layers for structural symmetry and perpendicular arrangement of adjacent layers for uniform properties in all directions;
- CLT offers several advantages as a construction material. These include low environmental impact, a high strength-to-weight ratio, ease and reduced time of installation, and aesthetic appeal. Furthermore, CLT structures are associated with lower carbon dioxide emissions compared to steel and concrete, reduced energy consumption during manufacturing, and enhanced resistance to fire, seismic actions, and thermal effects;
- CLT panels must be made from lightweight elements, but with superior resistance; for reduced costs, local wood resources could be used;
- The most commonly used wood species are softwoods, and less often fast-growing deciduous trees;
- The most commonly used CLT structures in house construction are those with three to five layers, less often those with seven or nine layers;
- The adhesives often used in the production of CLT panels are the structural ones, such as melamine-urea-formaldehyde, phenol-formaldehyde, isocyanate or polyurethane (PUR);
- The usual connections are those with metal connectors, followed by those with screws or direct joints in the CLT panel (in fold, with tongue and groove or in extension).

## References

1. ABNT NBR 7190, 2022. Timber Structures – Part 7: Test Method Structural cross laminated timber. Associação Brasileira de Normas Técnicas.
2. ANSI/APA PRG 320, 2025. Standard for performance – Rated cross-laminated timber. American National Standard.
3. ASTM D198, 2022. Test methods of static tests of lumber in structural sizes. ASTM International, West Conshohocken, PA, USA.
4. ASTM D4761-19, 2025. Standard test methods for mechanical properties of lumber and wood-base structural material. ASTM International, West Conshohocken, PA, USA.
5. ASTM E564-06, 2018. Standard practice for static load test for shear resistance of framed walls for buildings. ASTM International, West Conshohocken, PA, USA.
6. Bayramoglu, M.M., Demir, A., Birinci, A.U. et al., 2025. Effect of lumber quality grade on the mechanical properties and product costs of cross-laminated timber panels. In: BioResources, vol. 20(2), pp. 3519-3533. DOI: 10.15376/biores.20.2.3519-3533.
7. Bettarello, F., Gasparella, A., Caniato, M., 2021. The influence of floor layering on airborne sound insulation and impact noise reduction: A study on cross laminated timber (CLT) structures. In: Applied Sciences, vol. 11(13), ID article 5938. DOI: 10.3390/app11135938.
8. Brandner, R., Flatscher, G., Ringhofer, A. et al., 2016. Cross laminated timber (CLT): Overview and development. In: European Journal of Wood and Wood Products, vol. 74, pp. 331-351. DOI: 10.1007/s00107-015-0999-5.
9. Brandt, K., Wilson, A., Bender, D. et al., 2019. Techno-economic analysis for manufacturing cross-laminated timber. In: BioResources, vol. 14(4), pp. 7790-7804. DOI: 10.15376/biores.14.4.7790-7804.
10. BS EN 301, 2006. Adhesives, phenolic and aminoplastic, for load-bearing timber structures – Classification and performance requirements. Committee European de Normalization (withdraw). New version is BS En 301, 2023.
11. Buck, D., Hagman, O., 2018, Production and in-plane compression mechanics of alternatively angled layered cross-laminated timber. In: BioResources, vol. 13(2), pp. 4029-4045. DOI: 10.15376/biores.13.2.4029-4045.
12. Buck, D., Wang, X., Hagman, O. et al., 2016. Bending properties of cross laminated timber (CLT) with a 45° alternating layer configuration. In: BioResources, vol. 11(2), pp. 4633-4644. DOI: 10.15376/biores.11.2.4633-4644.
13. Bülbül, R., Keskin, H., Kaya, M. et al., 2025. Experimental and numerical investigations of glued cross-laminated timber beams produced with different wood species and glues. In: BioResources, vol. 20(2), pp. 4720-4745. DOI: 10.15376/biores.20.2.4720-4745.
14. Choi, C., Kojima, E., Kim, K. et al., 2018. Analysis of mechanical properties of cross-laminated timber (CLT) with plywood using Korean larch. In: BioResources, vol. 13(2), pp. 2715-2726. DOI: 10.15376/biores.13.2.2715-2726.
15. De Araujo, V., Aguiar, F., Jardim, P. et al., 2023. Is cross-laminated timber (CLT) a wood panel, a building, or a

construction system? A systematic review on its functions, characteristics, performances, and applications. In: Forests, vol. 14(2), ID article 264. DOI: 10.3390/f14020264.
16. Dungani, R., Sulistyono, Karliati, T. et al., 2023. Analysis behaviour of openings on full-size cross-laminated timber (CLT) frame shear walls tested monotonically. In: Forests, vol. 14(1), ID article 97. DOI: 10.3390/f14010097.
17. EN 14081-1+A1, 2011. Timber structures: Strength graded structural timber with rectangular cross section. Part 1: General requirements. European Committee for Standardization.
18. EN 15978, 2026. A harmonized method to assess the environmental performance of buildings. European Committee for Standardization.
19. EN 16351, 2021. Timber structures – Cross laminated timber – Requirements. European Committee for Standardization.
20. EN 338, 2016. Structural timber – Strength classes. European Committee for Standardization.
21. EN 388, 2009. Protective gloves against mechanical risks. European Committee for Standardization.
22. EN 408, 2010. Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties. European Committee for Standardization.
23. EN 408:2010 +A1, 2012. Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties. European Committee for Standardization.
24. Espinoza, O., Trujillo, V.R., Mallo, M.F.L. et al., 2016. Cross-laminated timber: Status and research needs in Europe. In: BioResources, vol. 11(1), pp. 281-295. DOI: 10.15376/biores.11.1.281-295.
25. Flores, N.R., Gentry, R., Stewart, L.K., 2022. Behavior and damage characterization of impulsively loaded cross-laminated timber panels. In: Applied Sciences, vol. 12(23), ID article 12076. DOI: 10.3390/app122312076.
26. François, J., 2010. Manufacturing cross-laminated timber (CLT). Technological and economic analysis. Report no 201001259-3257AAM, FP Innovations, Quebec, Canada. Available at: https://library.fpinnovations.ca/link/fpipub39323. Accessed on: May 21, 2026.
27. Gašparík, M., Das, S., Kytka, T. et al., 2024. Bonding characteristics of CLT made from silver birch (*Betula pendula* Roth.), European aspen (*Populus tremula* L.) and Norway spruce (*Picea abies* (L.) H. Karst.) wood. In: Forests, vol. 15(9), ID article 1656. DOI: 10.3390/f15091656.
28. Gezer, E.D., Birinci, A.U., Demir, A. et al., 2024. Determining the optimum layer combination for cross-laminated timber panels according to timber strength classes using artificial neural networks. In: BioResources, vol. 19(3), pp. 4899-4917. DOI: 10.15376/biores.19.3.4899-4917.
29. Hashemi, A., Quenneville, P., 2020. Large-scale testing of low damage rocking cross-laminated timber (CLT) wall panels with friction dampers. In: Engineering Structures, vol. 206, ID article 110166. DOI: 10.1016/j.engstruct.2020.110166.
30. Iezzi, S., Savini, F., Trizio, I. et al., 2023.

On the role of seismic damage tolerance on costs and life cycle of CLT buildings. In: Applied Sciences, vol. 13(16), ID article 9113. DOI: 10.3390/app13169113.

31. ISO 14040, 2006. Environmental management – Life cycle assessment – Principles and framework. International Organization for Standardization.
32. ISO 16696-1, 2019. Timber structures – Cross laminated timber – Part 1: Component performance, production requirements and certification scheme. International Organization for Standardization.
33. ISO 3131, 1975. Wood – Determination of density for physical and mechanical tests (withdraw). New version is ISO 13061-2, 2014. International Organization for Standardization.
34. ISO 9087, 1998. Wood determination of nail and screw holding power under axial load application. International Organization for Standardization, Geneva, Switzerland.
35. JAS 3079, 2019. Cross laminated timber. Japanese Agricultural Standard, Ministry of Agriculture, Forestry and Fisheries, Tokyo, Japan.
36. Li, H., Wang, L., Wei, Y. et al., 2022. Bending and shear performance of cross-laminated timber and glued-laminated timber beams: A comparative investigation. In: Journal of Building Engineering, vol. 45, ID article 103477. DOI: 10.1016/j.jobe.2021.103477.
37. Liew, K.C., Tan, Y.F., Albert, C.M. et al., 2022. Cross-laminated timber and glulam from low-density *Paraserianthes falcataria*: A look into densification and shear strength. In: Forests, vol. 13(10), ID article 1540. DOI: 10.3390/f13101540.
38. Ljunggren, F., Fredriksson, M., Johansson, N. et al., 2025. Cross-laminated timber: A state-of-the-art review of moisture, fire, acoustics, and energy-related aspects. In: Wood Material Science and Engineering, vol. 21(2), pp. 1224-1246. DOI: 10.1080/17480272.2025.2507145.
39. Loss, C., Davison, B., 2017. Innovative composite steel-timber floors with prefabricated modular components. In: Engineering Structures, vol. 132, pp. 695-713. DOI: 10.1016/j.engstruct.2016.11.062.
40. MacGavin, R.L., Dakin, T., Shanks, J., 2020. Mass-timber construction in Australia: Is CLT only answer? In: BioResources, vol. 15(3), pp. 4642-4645.
41. Moritani, F.Y., Martins, C.E.J., Dias, A.M.P.G., 2021. A literature review on cold-formed steel-timber composite structures. In: BioResources, vol. 16(4), pp. 8489-8508. DOI: 10.15376/biores.16.4.Moritani.
42. Ou, J., Chen, Z., Long, W. et al., 2024. Research on stability of CLT wall under uniform compression based on orthotropic plate buckling theory. In: Journal of Building Engineering, vol. 84(10), ID article 108571. DOI: 10.1016/j.jobe.2024.108571.
43. Palacio-Betancur, A., Hormozabad, S.J., Niman, C. et al., 2022. Compressive properties of cross-laminated timber panels made of hardwood tree species from the Appalachian region. In: Journal of Architectural Engineering, vol. 29(1), ID article 4022043. DOI: 10.1061/JAEIED.AEENG-1.
44. Pang, S.J., Lee, H.J., Ha, Y.S. et al.,

2025. Fundamental natural frequency and floor impact sound insulation performance of CLT slabs based on wood species and panel connections: An experimental study. In: BioResources, vol. 20(1), pp. 100-120. DOI: 10.15376/biores.20.1.100-120.

45. Pasca, D.P., Massaro, F.M., De Santis, Y. et al., 2024. Deformation level and specimen geometry in compression perpendicular to the grain of solid timber, GLT and CLT timber products. In: Engineering Structures, vol. 321(6), ID article 118972. DOI: 10.1016/j.engstruct.2024.118972.
46. Perković, N., Skejić, D., Rajčić, V., 2024. Numerical analysis of fire resistance in cross-laminated timber (CLT) constructions using CFD: Implications for structural integrity and fire protection. In: Forests, vol. 15(11), ID article 2046. DOI: 10.3390/f15112046.
47. Rajčić, V., Perković, N., Bedon, C. et al., 2020. Thermal and energy-efficiency assessment of hybrid CLT-glass façade elements. In: Applied Sciences, vol. 10(9), ID article 3071. DOI: 10.3390/app10093071.
48. Sandoli, A., D'Ambra, C., Ceraldi, C. et al., 2021. Sustainable cross-laminated timber structures in a seismic area: Overview and future trends. In: Applied Sciences, vol. 11(5), ID article 2078. DOI: 10.3390/app11052078.
49. SANS 8892, 2020. Standard for performance – Rated cross-laminated timber. South African Standards.
50. Syahirah, Y.A., Anwar, U.M.K., Sh, L. et al., 2025. The properties of Cross Laminated Timber (CLT): A review. In: International Journal of Adhesion and Adhesives, vol. 138, ID article 103924. DOI: 10.1016/j.ijadhadh.2024.103924.
51. Tian, Z., Gong, Y., Xu, J. et al., 2022. Predicting the average compression strength of CLT by using the average density or compressive strength of lamina. In: Forests, vol. 13(4), ID article 591. DOI: 10.3390/f13040591.
52. TS 1265, 2012. Sawn timber (Coniferous) – For building construction. Turkish Standards Institute, Ankara, Turkey.
53. Xie, W., Ding, Y., Wang, Z. et al., 2020. Testing and analysis of hemlock cross laminated timber. In: Wood Research, vol. 65(5), pp. 819-832. DOI: 10.37763/wr.1336-4561/65.5.819832.
54. Yang, S., Choi, G., Kim, J. et al., 2023. Comparison of mechanical properties according to the structural materials of lumber, GLT, CLT, and Ply-lam CLT. In: BioResources, vol. 18(4), pp. 6971-6985. DOI: 10.15376/biores.18.4.6971-6985.
55. Young, T., Barbu, M.C., Hindman, D. et al., 2016. Comparisons of the production standards for cross laminated timber (CLT) in Europe versus USA. In: World Conference on Timber Engineering, August 22-25, 2016, Vienna, Austria, pp. 4412-4419.
56. Zhang, Y., Nehdi, M.L., Gao, X. et al., 2020. Flexural performance of novel nail-cross-laminated timber composite panels. In: Applied Sciences, vol. 10, ID article 5983. DOI: 10.3390/app10175983.