Civil Engineering Research Journal
ISSN: 2575-8950

Juniper Publishers
key to the Researchers

Mini Review
Volume 16 Issue 1 - November 2026
DOI: 10.19080/CERJ.2026.16.555929

Civil Eng Res J
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# Beyond Structural Performance: Cross-Laminated Timber as a Multifunctional Building Envelope Material

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**Submission:** October 31, 2026; **Published:** November 23, 2026

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**Abstract**

Cross-laminated timber (CLT) has emerged as an important engineered wood product for low-carbon construction, with applications in walls, floors, roofs, and entire structural systems. Although CLT is frequently investigated from a structural perspective, its growing application in exterior walls and roofs requires a broader understanding of its role as part of the building envelope. In this context, structural capacity alone is insufficient: CLT assemblies must simultaneously control heat, air, and moisture transfer; maintain durability and fire safety; reduce operational and embodied carbon; and adapt to changing climatic conditions. These functions are strongly interconnected and depend not only on the CLT panel itself but also on insulation, membranes, cladding, joints, construction moisture, and environmental exposure. This mini review summarizes recent developments in CLT building-envelope research, with emphasis on thermal and hygrothermal performance, moisture durability, fire safety, and environmental performance. Future research should move from evaluating individual CLT properties toward integrated, climate-responsive, and experimentally validated approaches for multifunctional timber envelopes.

**Keywords:** Cross-laminated timber; CLT; Building Envelope; Mass Timber; Hygrothermal Performance; Moisture; Thermal Performance; Low-carbon Construction

## Introduction

The transition toward low-carbon and energy-efficient buildings is changing the role of building materials. Materials are increasingly expected to provide multiple functions rather than satisfying structural requirements alone. The building envelope is particularly important because it simultaneously influences structural integrity, heat transfer, moisture transport, airtightness, indoor environmental conditions, operational energy consumption, durability, and whole-building environmental impacts. Cross-laminated timber (CLT), manufactured from layers of lumber arranged approximately orthogonally and bonded into large panels, has become one of the most prominent mass-timber products. Its relatively high strength-to-weight ratio, prefabrication potential, rapid assembly, and ability to store biogenic carbon make it an attractive alternative to conventional construction systems. Recent reviews demonstrate increasing applications of CLT as walls, floors, and roofs and highlight the importance of considering CLT as part of an integrated construction system rather than simply as an engineered wood panel [1-3]. Life-cycle studies also indicate potential reductions in global warming impacts when CLT replaces more carbon-intensive structural materials, although results depend strongly on system boundaries, biogenic-carbon accounting, transportation, forest management, building operation, and end-of-life assumptions [4,5]. Therefore, this paper review how CLT can function reliably as part of a multifunctional, durable, and low-carbon building envelope beyond serving as a structural building material.

## Thermal and Hygrothermal Performance

CLT can contribute to envelope thermal resistance while also providing structural capacity. However, the energy performance of a CLT envelope depends on the entire wall or roof assembly rather than on the timber panel alone. Panel thickness, insulation type and location, air and vapor control layers, cladding, joints, and thermal bridges all affect overall performance. Experimental and numerical investigations of different CLT wall configurations have demonstrated the importance of wall composition and thermal bridges when determining effective thermal resistance [6]. The hygroscopic nature of wood makes moisture particularly important. CLT exchanges moisture with its surrounding environment, and temperature and moisture transport therefore need to be considered together. Recent research on highly insulated

CLT exterior walls has shown that vapor permeability, insulation materials, and initial moisture conditions can significantly affect drying and moisture safety [7]. Bio-based envelope configurations using wood-fiber insulation have also demonstrated promising moisture-regulating behavior, illustrating opportunities to combine CLT with other bio-based materials [8]. This coupling can influence both building energy consumption and indoor conditions. Recent simulations supported by field measurements indicate that CLT wall systems can contribute to favorable indoor hygrothermal conditions, while the composition of wall layers substantially influences moisture behavior [9]. Consequently, evaluating only steady-state thermal resistance or U-value provides an incomplete description of CLT envelope performance.

## Moisture, Durability, and Climate Resilience

Moisture remains one of the most important challenges for mass-timber envelopes. CLT panels may be exposed to precipitation during transportation and construction, plumbing leaks during operation, vapor diffusion, air leakage, or wind-driven rain entering through envelope defects. Excessive or prolonged moisture can contribute to dimensional changes, mold growth, biological degradation, and deterioration of connections or bonding systems. Reviews of mass-timber durability therefore emphasize moisture control throughout manufacturing, transportation, construction, and building operation [10]. Recent research has moved toward more detailed modeling of moisture transport. Kalbe et al. [11], for example, developed and validated an anisotropic hygrothermal model and highlighted the particular vulnerability of CLT end grain to water uptake. Their findings emphasize construction-phase protection, installation timing, and adequate drying before assemblies are enclosed. Field-laboratory investigations of CLT roof assemblies similarly demonstrate that construction protection and ventilated cavities can improve drying, whereas highly impermeable membranes can trap moisture and slow dry-out [12]. Future temperature, humidity, and wind-driven-rain conditions may change the moisture risks experienced by timber envelopes during their service lives. A recent study evaluating CLT walls under future Canadian climate scenarios showed that drainage-cavity ventilation can improve drying, but climate-specific risks remain, particularly in humid regions [13]. These findings suggest that CLT envelope design should increasingly move away from one-size-fits-all assemblies toward climate-responsive design strategies.

## Fire Safety and Integrated Envelope Performance

Fire safety remains another major consideration in CLT construction. Timber develops a char layer during fire exposure, but CLT introduces additional considerations related to adhesive performance, delamination, exposed surface area, and compartment fire dynamics. Large-scale studies and recent reviews indicate that protective encapsulation can delay CLT involvement in fire and that the amount and arrangement of exposed timber significantly affect fire behavior [14]. Importantly, moisture, thermal, fire, acoustic, and energy requirements should not be optimized independently. A recent state-of-the-art review emphasizes that these requirements can interact or even conflict. For example, envelope layers introduced for moisture or thermal control can affect drying potential, while coverings used for fire protection also change the thermal and hygrothermal configuration of the assembly [14]. The design challenge is therefore not simply to maximize one material property, but to identify assemblies that provide acceptable performance across multiple criteria throughout the building life cycle.

## From Passive CLT Panels to Multifunctional Envelopes

An important future direction is to treat CLT as the foundation of a multifunctional envelope system. CLT can potentially be integrated with bio-based insulation, advanced coatings, phase-change materials, high-performance membranes, photovoltaic systems, and embedded sensing technologies. Such systems could simultaneously provide structural support, thermal resistance, moisture buffering, renewable-energy generation, and environmental monitoring. Embedded temperature, relative-humidity, moisture-content, and heat-flux sensors could provide continuous information on envelope conditions. Coupling these measurements with building energy and hygrothermal models could enable early detection of moisture accumulation, evaluation of drying potential, and prediction of long-term deterioration. In the longer term, digital representations of CLT envelopes could be continuously updated using sensor measurements, creating a pathway toward digital-twin-enabled envelope management. Circularity is another emerging opportunity. Designing connections for disassembly and reuse could extend the carbon-storage period of timber products and reduce demand for virgin materials. Recent research on reusable timber systems and recycled CLT indicates substantial opportunities for incorporating design-for-reuse and circular-economy principles into mass-timber construction [15].

## Research Needs and Outlook

Future CLT research should increasingly examine the envelope as a coupled material–building–environment system. Four priorities are particularly important. First, long-term experiments under realistic combinations of temperature, humidity, solar radiation, precipitation, and extreme events are needed. Second, laboratory and field measurements should be integrated with validated heat-and-moisture and whole-building energy models. Third, the impacts of changing climate conditions should be incorporated into durability and service-life assessment. Finally, life-cycle carbon analysis should be connected with actual envelope durability, operational energy, maintenance, reuse, and end-of-life scenarios rather than treating embodied carbon independently. CLT has significant potential to contribute to low-carbon construction, but its future value extends beyond


How to cite this article: Qiuhua Lisa D. Beyond Structural Performance: Cross-Laminated Timber as a Multifunctional Building Envelope Material. Civil Eng Res J. 2026; 16(1): 555929. DOI:10.19080/CERJ.202.16.5559279

replacing concrete or steel. The greater opportunity is to develop multifunctional timber envelope systems in which structural performance, heat and moisture management, durability, fire safety, operational energy, embodied carbon, and intelligent monitoring are considered together. This transition from a structural panel to an integrated high-performance envelope system represents an important direction for building-materials and civil-engineering research.

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DOI: 10.19080/CERJ.202.16.5559279

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