



A review of the blast behavior of Cross-Laminated Timber (CLT) structures

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ABSTRACT

Recent advances in the use of mass-timber systems in contemporary buildings have made Cross-Laminated Timber (CLT) one of the most environmentally attractive materials for structural applications. Considerable progress has been made in understanding the fire resistance and seismic behavior of CLT structures; however, their response to accidental extreme loads, especially blast loading, remains insufficiently addressed. This study presents a comprehensive state-of-the-art review of the response of CLT structural elements and systems subjected to blast loading, covering experimental, analytical, and numerical investigations. Fundamental characteristics of blast loading and structural dynamic response are also reviewed. Special attention is given to dominant failure modes, including rolling shear, delamination, tensile failure, and localized crushing, which are influenced by the layered configuration of CLT panels. Experimental studies based on shock-tube and field-blast tests are reviewed, with emphasis on the effects of panel configuration, connections, and retrofitting strategies. Current modeling practices, including finite element analysis and equivalent single-degree-of-freedom approaches, are critically examined. Literature synthesis identifies major knowledge gaps, including the lack of standardized material models, limited experimental data, and insufficient design-oriented analytical tools. Finally, future research directions are outlined to support the development of performance-based blast-resistant design methodologies for mass-timber structures.

1. Introduction

The rapid expansion of mass-timber construction has altered the architectural and structural landscape over the past decade. Cross-Laminated Timber (CLT) is a leading engineered wood product that is revolutionizing modern construction, already prevalent in mid- and high-rise structures, and the latest developments are accelerating its entry into the next generation of tall timber buildings [1]. CLT is an advanced structural material offering a sustainable alternative to steel and concrete and is becoming the material of choice for numerous schools, residential blocks, office buildings and public facilities [2]. Its improved mechanical performance [3], excellent sound insulation properties [4], hygrothermal properties [5], sustainability [6], and prefabrication advantages (quick assembly on-site, cutting down on construction time and labor costs) have accelerated its application in Europe and other parts of the world. Table 1 shows various timber- and CLT-related standards used around the globe.

As the use of CLT has expanded, research and regulation have focused mainly on fire and seismic performance. Consequently, the

behavior of CLT in fire is now relatively well understood, whereas knowledge of its response to other extreme events has not developed at the same pace.

Research into its seismic performance has made significant progress, showing promising ways to dissipate energy, reliable connection designs, and good dynamic behavior [21,22]. These developments indicate that tall buildings made with CLT will likely appear soon, even in areas with high earthquake risk. The main challenge is not with regulations, since many seismic codes already allow for timber structures if they meet certain performance standards. The real obstacle is construction practices, especially in places like southern Europe, where reinforced concrete is the “normal” practice (considering durability, stability against seismic risks, and the cost-effectiveness of local materials) [23] and large timber buildings are still seen as unusual. On the contrary, countries such as Canada have proven the feasibility of hybrid mass timber systems under severe conditions [24,25]. For example, the Brock Commons building utilizes CLT floor panels, glulam columns, and concrete cores to achieve seismic performance and modern architectural demands [26]. However, despite the increased adoption of CLT

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Table 1
Timber and CLT related standards.

	Standard / Code	Title
International	ISO 16696-1 [7]	Timber structures — Cross laminated timber — Part 1: Component performance, production requirements and certification scheme
USA	ANSI/APA PRG 320 [8]	Standard for Performance-Rated Cross-Laminated Timber
USA	ANSI/AWC NDS [9]	National Design Specification for Wood Construction
USA	IBC [10]	Mass timber and the 2024 International Building Code (IBC)
Canada	CSA O86 [11]	Engineering Design in Wood
Canada	CWC [12]	Guide to Encapsulated Mass Timber Construction in the Ontario Building Code
European Union	EN 16351:2021 [13]	Timber structures, Cross-Laminated Timber Requirements
European Union	EN 1995-1-1 (Eurocode 5) [14]	Design of Timber Structures
European Union	EN 1995-1-2 (Eurocode 5) [15]	Structural Fire Design
Australia	AS 1720.1 [16]	Timber structures — Part 1: Design methods
Japan	JAS [17]	Japanese Agricultural Standard for CLT
Japan	AIJ Standard	AIJ Standard for Structural Design of Timber Structures
New Zealand	NZS 3603 [18]	Timber Structures Standard
China	GB/T 51226-2017 [19]	Technical standard for multi-story and high rise timber buildings
China	LY/T 3039-2018 [20]	Cross Laminated Timber

applications in structural engineering, a limited understanding exists of its behavior under accidental extreme loads, i.e., blast and impact [27].

Emerging design concepts for taller, more complex, and functionally critical timber buildings inevitably raise the question of blast resilience [28]. New CLT buildings are increasingly located in urban environments, are often assigned to higher importance classes, and may be used for residential buildings [29], public administration facilities [30], and transport infrastructure such as bridges [31], where accidental explosions cannot be dismissed as improbable. Blast loading is particularly relevant because it can expose weaknesses in CLT structures, such as delamination, rolling-shear sensitivity, and brittle behavior perpendicular to the grain. These aspects are known in static and seismic design, but they become more critical under the very short durations and high strain rates associated with explosions.

Timber is known for its clear strain-rate dependence of its mechanical behavior, especially in the case of impact and blast loads [28]. Existing experimental works on the behavior of solid timber demonstrated that increase in strain rate could lead to an increase in strength and stiffness properties of the material, but the level of the influence depended on the type of load, orientation, moisture content, density and wood species [29,30]. In CLT, the strain rate sensitivity was higher in case of high strain rate loads and corresponding failure mechanisms were different from those in quasi-static loading conditions [31]. Notably, the influence of the lamination [32], adhesive layers [33], orthotropic lay-up [34] and inter-laminate interaction [35] should be taken into account for GLT and CLT products. In some existing experimental works confirmed that CLT could demonstrate enhanced performance in case of high-rate loads. As reported in [36], higher loading rates increased peak resistance by 6–10% for spline joints and 9–19% for GLT-to-CLT connections. Poulin et al. reported a 28% increase in CLT resistance under blast loading, while stiffness remained largely unaffected [37]. Flores et al. reported significant strain-rate enhancement in impulsively loaded CLT panels, with the apparent flexural stiffness increasing by 1.3–7.2 times, although shear failure caused a substantial loss of resistance [31]. Experimental evidence on the strain-rate-dependent material and structural response of CLT remains limited compared with solid timber, highlighting the need for a critical

review of existing experimental and numerical studies under high-rate loading, particularly impact and blast loads.

The acknowledgment of these challenges is now beginning to surface at the European research level. COST Action HELEN [32] is an umbrella for the holistic design of taller timber buildings and recognizes robustness, multi-hazard analysis, and performance in exceptional loads as critical areas that warrant urgent attention in timber construction. In the working group 3, accidental situations like fire and earthquakes very discussed [32], but with a clear space being left for blast-related aspects as a separate task group. This is part of a wider trend that is moving away from CLT being perceived as simply a carbon-friendly material and is now being positioned as an option for structurally demanding applications [33] in which enhanced robustness is required.

Blast loading subjects structural members to high-intensity, short-duration pressure waves that can result in severe flexural, shear, and delamination failures [38]. Examples from various structural systems show that blast problems are real, not just theoretical.

For example, the RC structures often fail due to internal gas explosions. Further, steel frames have been found to bend excessively after accidental industrial blasts. In addition, masonry infills are sometimes thrown out during urban explosions, which can threaten the stability of buildings.

Primary failure modes in RC structures under blast loading are spalling, scabbing, crushing, bending, cracks, reinforcement rupture, cratering, punching, and flexural and shear failure [39,40]. These cases illustrate that even well-understood materials exhibit unexpected damage patterns under explosive loads.

Within mass timber, the available but limited evidence points to similar concerns [41]. This shortage of knowledge is a significant challenge for engineers and researchers seeking performance-based design strategies for CLT systems in safety-related applications.

To address these challenges, the following sections provide a systematic review of blast-loading characteristics, structural response mechanisms, and current analytical and numerical approaches relevant to CLT structures.

However, it needs to be mentioned that the influence of connection behavior on the overall response of CLT panels under blast and impact loading is an important topic but is not examined comprehensively in this review. Similarly, this review is primarily focused on the range of strain rates covered in the available literature and does not comprehensively address other loading scenarios, such as CLT wall systems subjected to combined in-plane compression and out-of-plane blast or impact loading.

2. Characteristics of blast loading and blast response relevant to CLT

Mourão et al. [41] have provided a list of works conducted on this specific subject (the structural element tested, method of blast loading generation) and reported in Table 2, Table 3, Table 4, Table 5, Table 6, and Table 7, where Z is the scaled distance expressed as the ratio of the geometric distance between explosive charge and target and the cubic root of the charge mass.

Table 2
Research focus: Dynamic material properties.

Timber element	Testing	$Z \left[\frac{m}{kg^3} \right]$	Ref	Year
Dimensional timber	Shock tube	9.6	[42]	2013
Light-frame walls	Shock tube	8.4–24.1	[43]	2015
CLT panels	Shock tube	6.6–35	[44]	2018
Light-frame walls	Shock tube	9.6	[45]	2013
GLULAM beams	Shock tube	6.2–33.5	[46]	2018

Table 3

Research focus: Retrofitting.

Timber element	Testing	$Z \left[\frac{m}{kg^{\frac{1}{3}}} \right]$	Ref	Year
Light-frame walls	Shock tube	6.5–33.7	[45]	2013
Light-frame walls	Shock tube	–	[43]	2016
GLULAM beams	Shock tube	5.7–7.1	[47–49]	2018
Light-frame walls	Shock tube	5.9–16.5	[50–54]	2016
GLULAM beams	Shock tube	6–7	[55]	2014
GLULAM beams	Shock tube	–	[56]	2019
CLT panels	Shock tube	5.1–7	[57]	2019

Table 4

Research focus: Connections.

Timber element	Testing	$Z \left[\frac{m}{kg^{\frac{1}{3}}} \right]$	Ref	Year
Light-frame walls	Shock tube	7.8–18.3	[50–54]	2016
CLT panels	Shock tube	6.9	[58]	2018
CLT panels	Shock tube	5.9–8.4	[59–61]	2019
Plain wood	Shock tube	6.6	[62]	2020
CLT panels	Shock tube	6–7.4	[63]	2019
GLULAM beams	Shock tube	6.27–6.67	[64]	2020

Table 5

Research focus: Experimental and analytical modelling.

Timber element	Testing	$Z \left[\frac{m}{kg^{\frac{1}{3}}} \right]$	Ref	Year
Light-frame walls	–	–	[57]	2013
GLULAM beams	Shock tube	6.5–7	[55]	2014
GLULAM beams	Shock tube	6.5–33.5	[47–49]	2018
CLT panels	Field Test	5.2–9.3	[65]	2018
CLT panels	–	–	[59–61]	2019
CLT panels	Field test	0.59	[66]	2026
CLT panels	Blast tank	0.46–0.69	[66]	2026

Table 6

Research focus: Failure modes.

Timber element	Testing	$Z \left[\frac{m}{kg^{\frac{1}{3}}} \right]$	Ref	Year
GLULAM beams	Shock tube	7.1–10.7	[43]	2014
Light-frame walls	Shock tube	–	[50–54]	2016
Light-frame walls	Shock tube	–	[67,68]	2017
GLULAM beams	Shock tube	–	[47–49]	2018

2.1. Fundamentals of blast loading and structural response

Blast loads represent an extreme dynamic action characterized by high pressure amplitudes, rapid pressure rise, and very short loading durations (Fig. 1). Unlike conventional actions such as wind or earthquake loads, the effects of blast loading generally last only a few milliseconds. Blast loads are therefore characterized by a rapid rise and decay of pressure, typically represented by a Friedlander waveform (Eq. 1).

$$p(t) = p_s \left(1 - \frac{t}{t_d} \right) e^{-\frac{t}{t_d}} \quad (1)$$

where

$t \geq 0$; $p(t)$ is the overpressure at time t ; p_s is the peak overpressure; t_d

Table 7

Research focus: Assembly response.

Timber element	Testing	$Z \left[\frac{m}{kg^{\frac{1}{3}}} \right]$	Ref	Year
CLT panels	Shock tube	23.7	[69]	2017
CLT panels	Field Test	5.3–7.5	[70]	2018
SIP panels	Shock tube	5.9–15.6	[71]	2021
CLT panels	Shock tube	3.4–6.5	[72]	2020

positive phase duration; t is the time after shock arrival; e is the base of the natural logarithm.

The response of a structural component depends on the ratio of load duration to its natural period, the boundary conditions, and material properties [75].

Moreover, an ideal Friedlander waveform has been employed by researchers to describe the major phases involved in the rapid pressure increase from the positive leading wave to the exponential decay, as well as the negative phase [73]. The important parameters that influence the level of blast loading are charge weight, stand-off distance, and surrounding geometry [76]. Reflection from structural surfaces can be an important factor in increasing the applied pressure, especially on the façade and vertical load-bearing structures [77].

The extent to which a structure responds to a blast load depends on the relative duration of the blast wave to the natural period of the structure. This is usually characterized by the impulsive, dynamic, and quasi-static regions of response [78]. The impulsive region describes a situation in which the duration of the blast wave is significantly smaller compared to the natural period of the structure and is mainly dependent on impulses and inertia forces. However, for load times equivalent to or greater than the natural period, there will be dynamic and quasi-static effects on the structure [40]. Therefore, similarly as in seismic design, the calculation of the natural periods and mass participation factors of the structure becomes essential in designing a structure to be blast-resistant.

Boundary conditions, force paths, and energy dissipation are essential in understanding the response of structures to blast loads. A structural component may undergo large deformation, acceleration, and localized stresses due to being subjected to blast loads. The blast loading on a structural object is mainly analyzed through explosive field testing and shock tube testing, as reported in Table 8.

Other studies suggest that single-degree-of-freedom (SDOF) representations are generally used to estimate global and component responses of structures [85]. However, there is a need to calibrate these representations when dealing with non-isotropic materials, for example, timber.

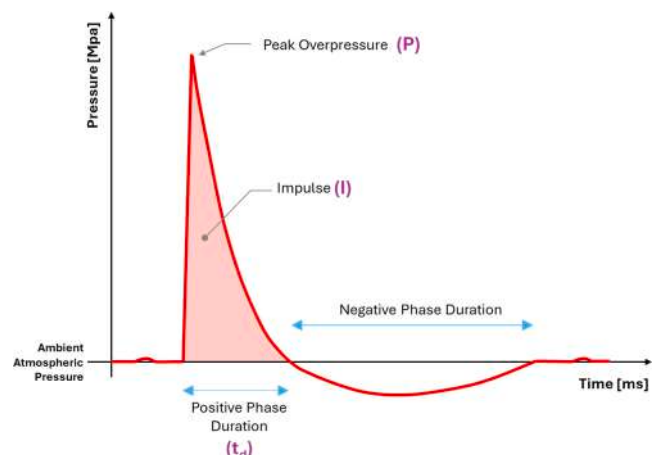


Fig. 1. Blast load (typical blast wave) – adapted from [73,74].

Table 8

Comparative evaluation of explosive field testing and shock tube testing for blast loading studies.

Aspect	Explosive Field Tests	Shock Tube Tests
Purpose	Real detonation of explosives to assess structural response under realistic free-field blast conditions [66,70].	Laboratory-based generation of blast waves using compressed gas or small charges to simulate blast loading in a controlled environment [66,79].
Blast Source	Actual high explosive charges detonated in open field/test range. [70]	Shock tubes produce blast waves with gas [80] or controlled small explosive charges [81].
Realism of Load	Very high: closely replicates real blast wave profiles and interaction with structures at full-scale [70,82,83].	Moderate to high: approximates blast loads (especially far-field), but conditions are idealized.
Size/Scale of Specimens	Can test full-scale or large structures because the blast source is unconstrained [70, 83].	Limited by shock tube cross-section; often component-level or small subassemblies [66,79].
Environmental Control	Low: environmental conditions (wind, terrain) influence result [73].	High: conducted in lab; repeatable and controlled [66,79].
Reproducibility	Low/Variable: identical blasts are hard to repeat due to explosive variability and setup conditions.	High: shock tube parameters are adjustable and repeatable across tests [84].
Safety & Logistics	High risk & complex: needs specialized explosive handling, remote ranges, safety protocols, and permits [82,84].	Lower risk: no large explosives; safer lab environment [84].
Cost	Very high: explosive charges, large spaces, instrumentation, personnel [84].	Moderate to low: laboratory setup and instrumentation but no explosives handling logistics [84].
Data Quality	Rich real-world data including fragmentation and secondary effects [82].	High precision in pressure/time measurements [82].
Duration/Pressure Range	Can achieve very large peak pressures and wide range depending on charge and standoff [82].	Limited by tube design; positive duration and peak pressures are tied to tube geometry [84].
Use Cases	Full-scale validation, certification, real blast scenario understanding [82].	Fundamental material/element behavior studies, model validation, comparative testing [82].

In [86], the authors conducted sensitivity analyses and found that SDOF models are valid only when boundary connections remain elastic and at least 10 times stiffer than the wood member; otherwise, MDOF analysis is required for accurate behavioral prediction.

In the case of brittle or layered materials like timber, the strain rate sensitivity and orthotropic properties have a significant influence on failure mechanisms, making them susceptible to accidental or deliberate blast explosions [87]. The possibility of collapse of tall mass timber buildings under blast loads poses not only a threat to the safety of the building occupants but also to the integrity of the surrounding infrastructure [87].

Although, in timber, higher strain rates are beneficial for enhanced strength and stiffness properties, they commonly cause failures due to brittleness or ductility [88], especially in the case of perpendicular tension to the grain and shear stresses.

Studies have also indicated that engineered wood products (EWPs), especially CLT, possess favorable mechanical properties [37,89–92] in blast situations. The lower variability of mechanical properties in CLT panels compared with dimensional timber can improve design accuracy and supports their potential use as blast-protection components [28].

The deformation and failure mechanisms of CLT panels subjected to blast loads are affected by interlayer interactions, bond line performance, and panel configuration properties. These properties determine

the behavior of the layers in a composite material subjected to severe loading conditions. Consequently, CLT panels display certain characteristics of delamination and energy dissipation.

The stress wave generated due to blast can result in interlayer debonding, rolling shear failure, and connection failure(s), which cannot be satisfactorily addressed using static analysis. The performance of mechanical fasteners and steel connectors is particularly important, as these often control the energy dissipation and failure in timber structures [93].

For tall mass timber structures, the design requirements for blast loading are a challenge at multiple scales, from the design of individual elements to the structural system. The potential collapse of a tall building due to localized element failure, contributed by column failure, wall failure, floor system failure, or failure by load redistribution/progressive collapse, can result in risks not only to the building inhabitants but also to surrounding infrastructure [41]. The reduced weight of a building due to the use of timber, which makes it more resilient during an earthquake, could result in high accelerations and displacements when a building is subjected to a blast load.

Comprehensive research already has been done in recent years to provide a thorough framework for the blast resistance assessment of steel and reinforced concrete structures, while similar studies on timber structures are relatively less explored [94]. Notably, the pressure-impulse (PI) diagrams, equivalent SDOF, and nonlinear finite element analyses can be used for the blast-resistant design. However, these models require calibration through targeted experimental validation. High-fidelity numerical analysis is also required to enhance their accuracy. These models can then be used to develop accurate design guidelines.

Another parameter is the Dynamic Increase Factor (DIF), which is often used to measure how materials respond to rapid loading, like blasts or impacts. Understanding the DIF is important for designing and analyzing structures in the context of explosives safety [95].

It is the ratio of dynamic (compressive/tensile) strength ($f_{m,dyn}$) to static/quasi-static strength ($f_{m,stat}$) [96]. It can be written as (see Equation 2)

$$DIF = \frac{f_{m,dyn}}{f_{m,stat}} \quad (2)$$

Therefore, it indicates how much stronger a material appears at high strain rates. It has been widely adopted to evaluate the strain rate effect of concrete-like materials [96].

Most structural materials normally have their strengths increase when subjected to rapid loads because of the influence of rate-sensitive fracture mechanisms [97], viscoelastic behavior [98], and the finite time required for crack initiation and propagation, which limits crack development under high loading rates [99]. In the case of concrete, with respect to compressive loading, the strength improves by 6–20 % in the case of low strain rates, 1.45 times for moderate strain rates, and can improve up to 3–4 times for very high strain rates [96]. With regard to tensile loading, the concrete material is very sensitive to changes in strain rate, with the strength improving by 5–17 % per log strain rate increase, and having typical DIFs of 2–4 [96].

For CLT, strain-rate effects do exist, although they are usually small since the behavior is primarily governed by its orthotropic and layered composition, which leads to an increase in dynamic stiffness at high strain rates [31].

For CLT panels subjected to explosive loadings, the DIF was found to be around 1.28 according to [37], whereas for glulam beams, the DIF was found to be 1.14 according to [100]. Moreover, [101] performed both static (Fig. 2.a) and dynamic tests (confined environment (Fig. 2.b, Fig. 2.d, Fig. 2.e, Fig. 2.f) and open air (Fig. 2.c)), and have determined that the DIF is dependent on the dominant mode of failure; an increase (1.55) occurs due to wood crushing, but no increase occurs due to fastener rupture.

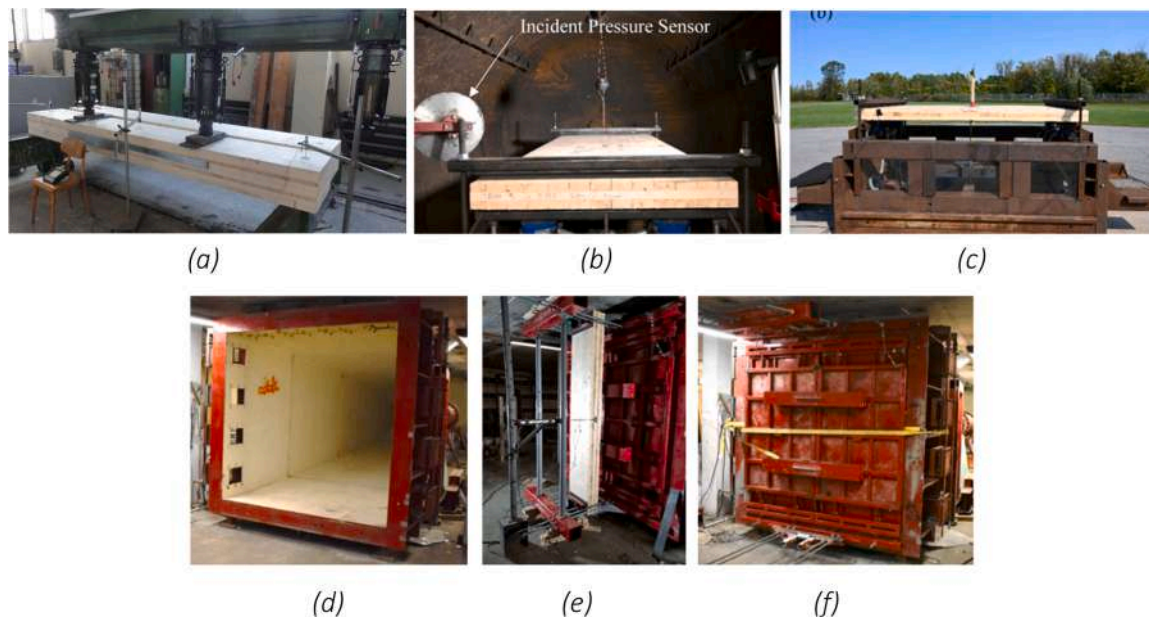


Fig. 2. (a) Static test [102]; dynamic test setups: (b) blast tank setup with CLT [66], (c) outdoor test on CLT [66]; and (d) Shock tube without sample [79], (e) CLT to be tested in shock tube [79], and (f) CLT sample inside shock tube [79].

Unlike homogeneous materials, CLT's mechanical behavior is controlled by several mechanisms, including rolling shear, longitudinal shear, and flexural modes, which influence each other during the loading process, with each mechanism having its own strain rate sensitivity [31].

However, the mechanical behavior of CLT differs from that of homogeneous materials because the behavior is governed by multiple interacting mechanisms with varying strain rate dependencies, as seen from the variation in DIF and its dependency on configuration and modeling considerations. DIF values reported in the range of 1.12–1.57 based on SDOF models and 1.05–1.43 from numerical simulations, highlighting the variability of the dynamic response [103].

The GLT panels exhibited increased strength resistance to simulated blast loading, with strength increase factors of 1.6–1.9 and a DIF improvement factor of 1.1 at a strain rate of 0.2 s^{-1} . The failure modes were similar both in static and dynamic cases, and the tension flexural mode prevailed. The one degree of freedom model provided correct calculations for the panels [104].

2.2. Mechanical behavior of CLT under dynamic and impact loads

CLT response under high-rate dynamic actions, such as impact and blast loading, is still not well understood [77]. These actions involve high strain rates, stress-wave propagation, and localized failure modes that differ significantly from those observed under static or seismic loading [98]. Under dynamic loading, increased strain rate may increase strength and, in some cases, stiffness in CLT, and this effect can be expressed through the DIF [64]. Although the DIF for CLT is lower than that of metals and concrete, even modest strength increases may influence blast resistance because of the short loading duration. Therefore, understanding the high-rate response of CLT requires careful consideration of bond-line behavior, which plays a key role in structural response [100]. CLT relies on adhesives to transfer shear between orthogonally oriented lamellae. Shear stresses and stress-wave reflections caused by impact and blast loading may therefore trigger bond-line failures. Experimental studies show that strength degradation in CLT under impact loading, particularly at elevated temperature, can occur at adhesive interfaces rather than within the timber itself [101].

Another known failure mode of CLT is failure [105,106]. Rolling shear failure occurs essentially in lamellae running in a direction normal

to the main stress orientation and is characterized by a lower shear strength and stiffness. In cases of blast or impact loads, rolling shear failure may readily develop, thereby reducing stiffness, increasing energy absorption, and subsequently reducing load-carrying capacity. Panels made of CLT may be sensitive to rolling shear failure based on characteristics such as thickness, type of species, moisture, and arrangement [107].

A limited impact test conducted on CLT panels shows that such systems possess the capability of dissipating a large amount of energy. The mechanisms identified for the dissipation of such energy are the localized crushing of wood fibers, plastic deformation, rolling shear failure, and delamination of layers. Unlike other materials that possess the capability of failing catastrophically, there is something special about CLT, as it possesses the capability of having a failure tolerance mechanism, where load redistribution occurs as individual lamellae or interfaces fail.

However, there are some challenges in the scalability and reproducibility of the results of the experiments. Impact tests on CLT panels show that there is a significant scatter introduced by the natural variability of the materials, the strength of the adhesives used, and the manufacturing process. Furthermore, the current studies are at the panel level, and hence the results will not be scalable to the construction level of high-rise buildings. The scalability and boundary conditions of the panels to the surrounding structural frames have no solution at the current stage.

In a modeling approach, the response of the CLT to impact and blast loading can be described by employing advanced numerical techniques. Equivalent SDOF systems of lower fidelity can be employed as a pre-processing step to evaluate the system response, but they cannot accurately represent the interlaminar failures, roll-shear failures, and peeling failures. Finite element analyses, which can account for complex material properties, strain-rate effects, and adhesive-layer behavior through cohesive-zone models, are currently employed to model the response of the CLT to severe loading.

Main dynamic failure modes in CLT under high-rate or impact loading can be categorized into:

(1) *Rolling Shear Failure*: Rolling shear failure in CLT (Fig. 3), typically occurs within the cross or transverse layers where the wood demonstrates relatively low shear strength perpendicular to the grain.

During dynamic or impact loading, cracks initiate and propagate



Fig. 3. Rolling shear failure [108].

along the wood fiber planes in these transverse lamellae as a result of elevated shear stresses caused by bending. Since the outer longitudinal layers possess greater strength in both tension and compression, damage is primarily concentrated in the cross layers. Consequently, rolling shear failure is the predominant failure mode observed in dynamic bending and impact tests on CLT panels [105,106].

Notably, Glasner et al. reported having achieved rolling shear strength and modulus of Australian *Eucalyptus nitens* CLT, which ranged from 2.8 to 3.4 MPa and 54.3–67.9 MPa, exceeding characteristic values and matching European softwood CLT standards [105]. Whereas the main failure mode was rolling shear failure in the cross-layer, characterized by shear cracking in the transverse lamellae under planar shear loading.

(2) *Delamination or Inter-Layer Separation* (Fig. 4): Delamination failure in CLT occurs when the adhesive bond between the neighboring lamellae fails, resulting in the separation of layers along the glue lines [109]. When subjected to dynamic or impact loads, high interlaminar stresses and strain rates can easily exceed the adhesive strength, resulting in the sudden separation of the layers. This failure mechanism can cause a substantial reduction in the load transfer between the layers, resulting in the sudden loss of stiffness and the rapid reduction in the overall load-carrying capacity of the CLT panel.

(3) *Tensile Rupture* (Fig. 5): Tensile rupture in the outer layers of CLT panels occurs when they are subjected to high bending stresses due to dynamic or impact loads. Fast loading results in high flexural tensile stresses in the outermost layers, resulting in sudden cracks and splits in the wood along the grain. This type of failure is normally in the form of long cracks along the board, and it is more sudden in dynamic loading because there is less opportunity for the stress to spread out. Sometimes the tensile failure in the middle layer can also be observed, as in the case of [111].

(4) *Local crushing/compression/indentation* (Fig. 6): The local crushing or indentation is created at the point of contact during the impact loading due to the high concentration of compressive stresses [112]. The wood fibers in this area experience localized compression and shortening, resulting in a permanent indentation. This localized crushing often serves as the initiation point for other failure modes, such as rolling shear failure in the transverse layers or delamination failure between the lamellae, as the impact damage continues to propagate through the CLT panel.

Overall, CLT exhibits promising energy-dissipation and damage-tolerance properties under dynamic and impact loading. Nevertheless,

its blast resistance is strongly influenced by interlaminar behavior, rolling-shear capacity, bond-line performance, and panel layout configuration. The strain-rate sensitivity of timber and adhesives, together with interface-related failure modes such as delamination, requires dedicated experimental investigation and advanced modeling approaches. Focused research in this area is essential to support the safe and reliable use of mass-timber structures in blast-prone environments.

2.3. Connections

In CLT construction, a connection (Table 9) is the joint where two or more structural components, such as panels, beams, columns, or foundations, are joined to ensure structural integrity. Connectors (Table 9) are the physical fastening devices [114] used to realize these connections: including screws, bolts, steel plates, brackets, nails, and other proprietary systems. Both connections and connectors play critical roles in CLT construction.

Sigong and Chui [132] have tested flexural behavior of panel-to-panel connections. The results showed that panel-to-panel connections provided very limited moment transfer, with rotational stiffness only 2.2–6.1% of intact CLT beams. Increasing the number of screws significantly improved stiffness and capacity, while screw diameter and spline thickness had smaller effects.

In [133], it has been found that CLT connections behave very differently under the two out-of-plane load conditions. Under compressive loading (OPE), capacity was governed by crushing of the wall panel wood fibers and was significantly higher on average 2.3 times (wall-to-floor) and 1.7 times (wall-to-foundation) greater than under tensile loading. Changing wood species from Spruce to Douglas-Fir increased OPE load capacity by approximately 24–29%. Under tensile loading, failure was controlled by nail withdrawal on the wall side, and only about 40% of the nails contributed to capacity, indicating a 60% inefficiency.

In- and out-of-plane lateral loading tests performed by Revani et al. (2021) [134] showed that CLT wall-to-floor angle bracket connections performed in a ductile manner under uplift and in-plane shear, while small-diameter and fully threaded screws improved strength and stiffness, though fully threaded screws reduced ductility and out-of-plane loading could cause panel splitting.

The tension and shear behavior of CLT wall-to-foundation screwed connections has been investigated by Feng et al. (2026) [135]. According to the authors, the connections behaved better in tension than in shear. It is pertinent to mention here that the angle bracket had up to 60% and 40% more strength and stiffness, respectively, than the other connections, and the proposed model predicted well. Furthermore, the authors indicate that theoretical analysis demonstrates the reduced shear performance of the connection is primarily due to steel plate bending and substantial screw rotation.

The influence of beam-panel connections on the vibration of CLT floors under multi-person loading was investigated by Zhang et al. (2023) [136]. The results showed that the size of the screws had little effect, but increasing the distance between the screws increased the

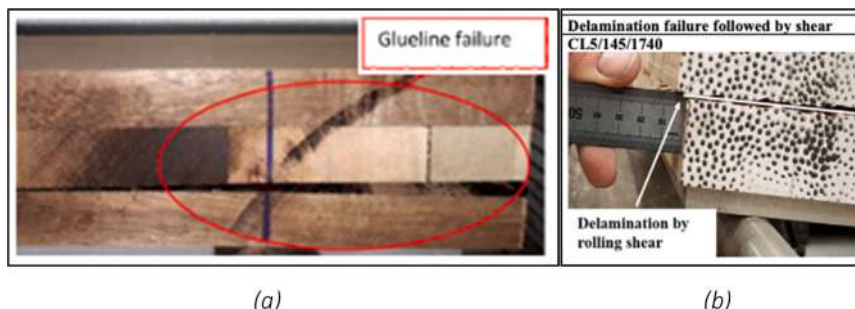


Fig. 4. Glue line [108] or delamination failure [110].

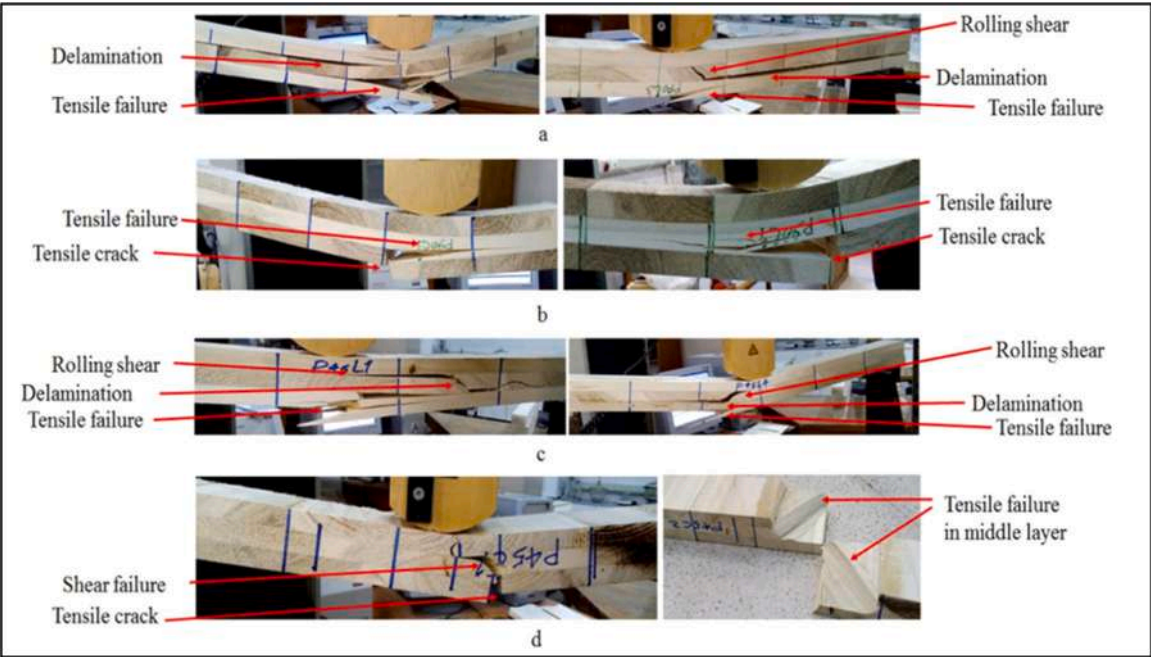


Fig. 5. The combination of tensile failures along with other failure modes [111].



Fig. 6. Compression/crushing failure [113].

natural frequency by 4.3% and decreased the vibration dose value by 38.3%. A theoretical model and design method for vibration serviceability were also presented by the authors.

Keipour et al. (2018) [137] have studied the performance of beam-to-column connections under hogging bending. The authors highlight to have obtained good ductility and rotation capacity, meeting Eurocode requirements, and achieved much higher negative bending capacity than bare steel connections. Various wall-to-roof connections are reported in [138].

The Integrated Panel Core (IPC) [139] is a rectangular hollow cross-laminated timber (CLT) core designed to function as a vertical cantilever, providing resistance to lateral loads in buildings. As shown in Figs. 8 and 9, tension forces are distributed around the panel joints and transferred to the foundation through vertical Laminated Veneer Lumber (LVL) brackets and replaceable steel hold-down bars, which enable the structure to rock during seismic events. Structural analysis demonstrates a safety factor of 1.27 against factored loads, and

Table 9

Types of connections and connectors used in CLT.

Connections in CLT	Connectors Used in CLT
Diaphragm connections [115]	Self-tapping screws (fully / partially threaded) [116]
Panel-to-panel [110]	Wooden connectors [117]
Wall-to-floor [112]	Dowel-type fasteners [118]
Wall-to-roof [114]	Bolts [119]
Floor-to-floor [120]	Lag screws [121]
Wall-to-foundation [117]	Nails (ring-shank / smooth-shank)
Beam-to-panel [119]	Nail plates [119]
Wall-to-ceiling [113]	Angle brackets [121]
Beam-to-column [120]	Hold-down brackets [122]
Column-to-floor [121]	Steel plates [123,124]
Integrated panel core (IPC) [123]	Concealed connectors [125]
	Ring connectors [126]
	Shear keys [127]
	Dissipative Connector [128,129]
	Timber rivets [130]
	Threaded rods [131]

wind-induced drift remains within acceptable limits.

Sullivan et al. (2018) [115] have performed monotonic and cyclic tests on 2.44 m CLT diaphragm shear connections with 8 mm and 10 mm self-tapping screws. It has been observed that the experimental yield strengths were 2.1–6.1 times higher than the factored design values from U.S. and Eurocode provisions. The half-lap connections with angled and vertical screws demonstrated high initial stiffness and ductile post-peak behavior, indicating strong seismic performance.

In Pomaroli A. and Kraler A. (2023) [117], the reference geometry, for equal height beams of 160 × 160 mm, had a capacity that was 66% greater than that of a basic tenon form. After failure of the tenon base, about 90% of the ultimate loads are transferred by the flanks. The novelty of this study is the design and validation of a metal-free LVL-based “double dovetail” connector for wall-ceiling joints of CLT construction (Fig. 7). The study demonstrated that optimized wood-wood geometry is effective for efficient load transfer and high structural performance.

The performance of mechanical fasteners and steel connections is



Fig. 7. Wood-wood system connections [117].

particularly important, as these often control the energy dissipation and failure in timber structures [93].

As reported in Zhang et al. (2020) [121], the connection stiffness and moment capacity were primarily influenced by the number of used screws. Notably, Screw diameter and spline thickness had a smaller influence, while longer screws reduced stiffness and capacity with higher variability. The overall moment transfer was found to be very limited (less than 6% of intact beams).

The experiments conducted by Azinović et al. (2022) [140] have shown that all tested self-tapping screw CLT connections (Fig. 8) failed in a brittle manner, predominantly through plug shear, sometimes combined with row or step shear self-tapping screw connections. Load-bearing capacity increased with specimen width (up to about 45%) and screw penetration length, while stiffness was strongly influenced by screw length (up to about 70% increase) but only marginally by CLT layup in self-tapping screw connections. Connections loaded perpendicular to grain exhibited significantly lower capacity (around 60% of parallel cases) and stiffness in self-tapping screw connections. The assessed brittle failure model ([141,142]) generally overestimated capacity and showed poor predictive performance, indicating the need for improved design approaches.

Pan et al. (2023) [143] have studied the performance of the CLT shear walls with self-tapping screw connections; tests demonstrated that the connections were 2.8–3.6 times stronger than what the Canadian timber design standard predicts. Tests on 26 CLT shear walls showed that wall strength and displacement capacity went up as the number of screws, hold-downs, spline joints, and connected panels increased.

However, strength dropped when the aspect ratio was higher. These results help improve connection design and offer useful data for calibrating numerical models of CLT shear wall behavior.

Wright et al. (2023) [144] investigated the cyclic behavior of cross-laminated timber (CLT) shear wall hold-down connections using mixed-angle self-tapping screws (Fig. 9).

Their findings indicate that the combined use of inclined and 90° screws results in high strength, and it found to be between 470–593 kN, high initial stiffness (212–269 kN/mm), and notable ductility ($\mu = 10\text{--}20$). Additionally, the study demonstrates that current design methods yield conservative strength predictions relative to experimental outcomes.

The experimental results shown in Dong et al. (2020) [122] indicated that nailed CLT hold-down connections have a moderate to high degree of ductility with ductility factors varying from 2.7 to 4.3 for 3 mm brackets and 4.7–6.3 for 10 mm thick plates with longer nails. The overstrength factors varied from 1.45 to 1.62, while similar yield strengths were obtained for monotonic and cyclic loads without brittle failure of the brackets.

As in Fig. 10, Schmidt, T. (2017) [127] experimentally investigated Beech laminated veneer lumber (LVL) shear-key contact joints for in-plane CLT diaphragms and found that they provide high stiffness, ductile load–displacement behavior, and load capacities up to about 85 kN for 40-mm keys with slenderness ratios ≥ 2 . A minimum spacing of 11 times the key thickness prevented brittle CLT shear failure, and a simplified design model based on compression perpendicular to the grain showed good agreement with test results.

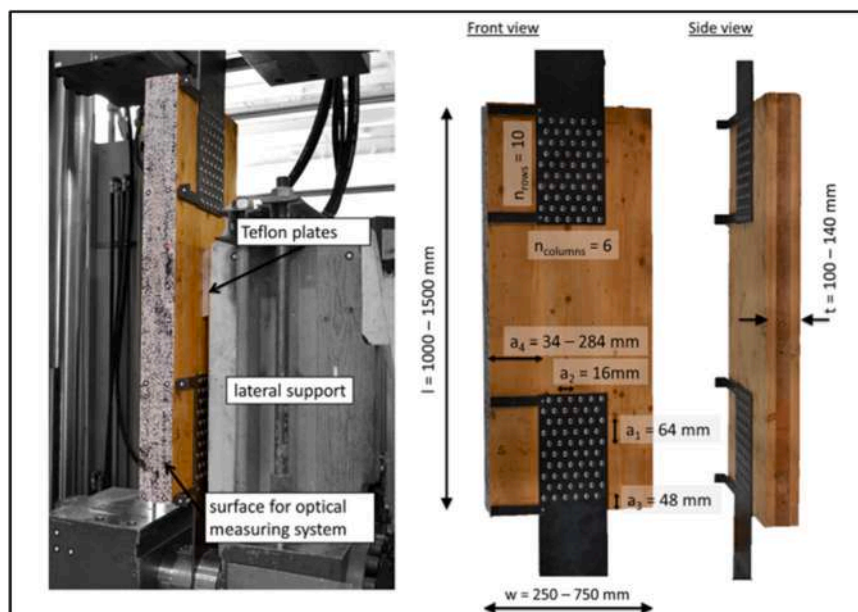


Fig. 8. Test specimen with denotations [140].

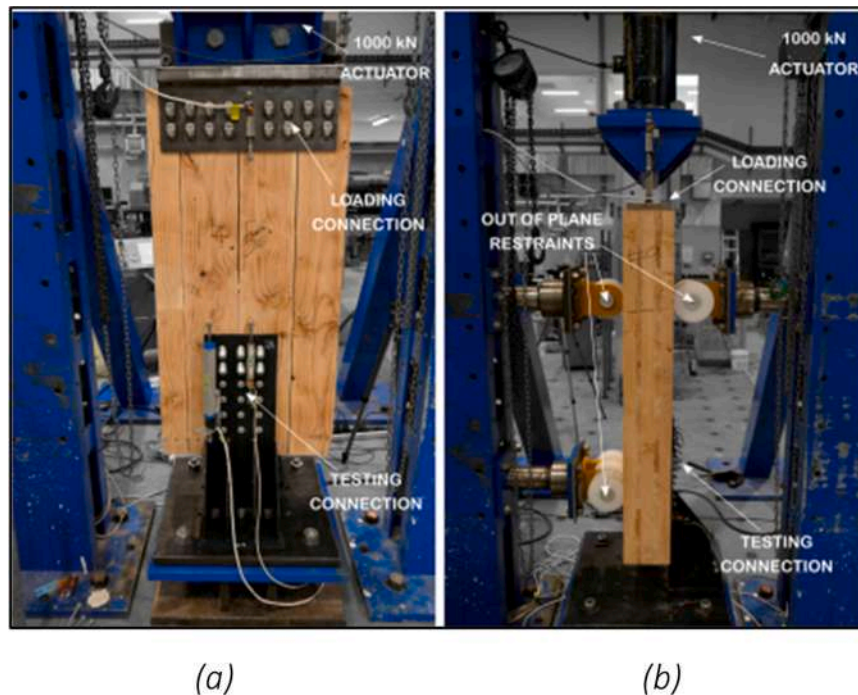


Fig. 9. Experimental setup with vertical load: (a) Configuration 1, 2, 4, 5; and (b) Configuration 3 with out of plane restraints [144].

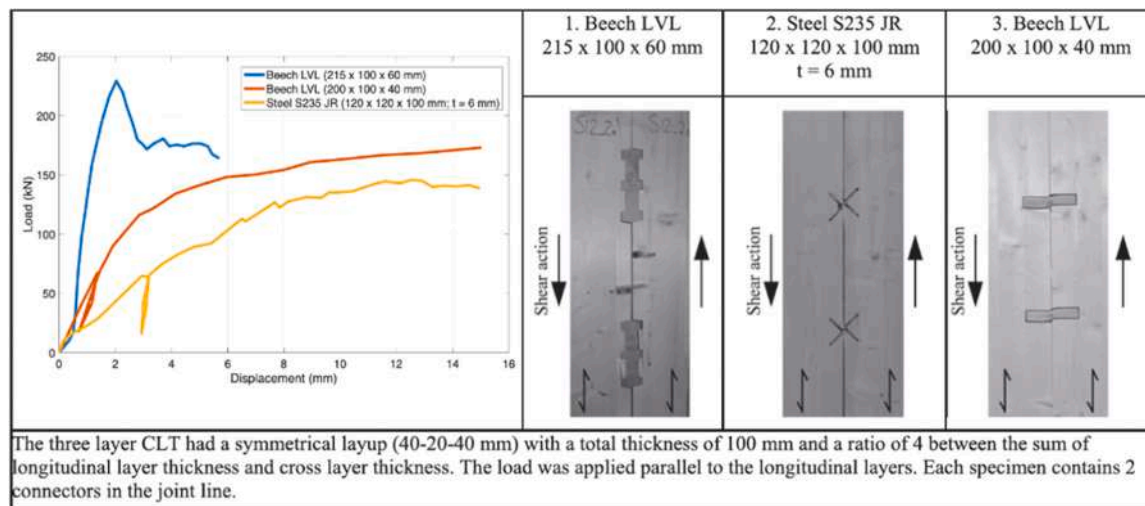


Fig. 10. Load displacement curve (reproduced from [127]) of different types of joints.

Fanti et al. (2025) [126] have introduced the RING60T (timber-to-timber) and RING90C (timber-to-steel/concrete) ring connectors, developed for prefabricated cross-laminated timber (CLT) structures. It was also evident from the results obtained in monotonic tensile and shear tests that both connectors possess strength and stiffness comparable to conventional angle brackets and hold-downs and display significant elastic-plastic behavior and multi-directional capacity. Failure modes identified during the tests include screw withdrawal and tensile rupture. The connectors showed consistent performance in both tensile and shear loading and can thus be used for wall-to-floor, wall-to-foundation, and hybrid connections.

Kraler et al. (2014) [145] demonstrated that the SHERPA-CLT-Connector meets essential structural and assembly requirements, achieving maximum specimen load values. The bearing capacity of this connector satisfies the structural criteria necessary for application in a four-storey solid timber building.

Scotta et al. (2016) [128] an innovative dissipative steel “X-bracket” connection (Fig. 11) for CLT shear walls, which was designed to offer high ductility together with high capacity of energy dissipation under cyclic loading conditions. The experimental tests revealed that the proposed X-bracket exhibited high initial stiffness, similar strength to traditional hold-downs and angle brackets, very large displacement capacity, negligible pinching, as well as low degradation of the strength capacity. The use of the proposed X-bracket in CLT shear walls resulted in a considerable enhancement of ductility, a reduction of the degradation of the capacity, as well as an increase of the capacity of energy dissipation, which allows even large single-panel shear walls to be assigned to the High Ductility Class as defined by Eurocode 8.

Yang et al. (2021) [131] have studied the behavior of axially loaded screwed-in threaded rod connections in CLT structures with and without self-tapping screw reinforcement. It was observed that the withdrawal capacity and slip stiffness were high, and the performance increased

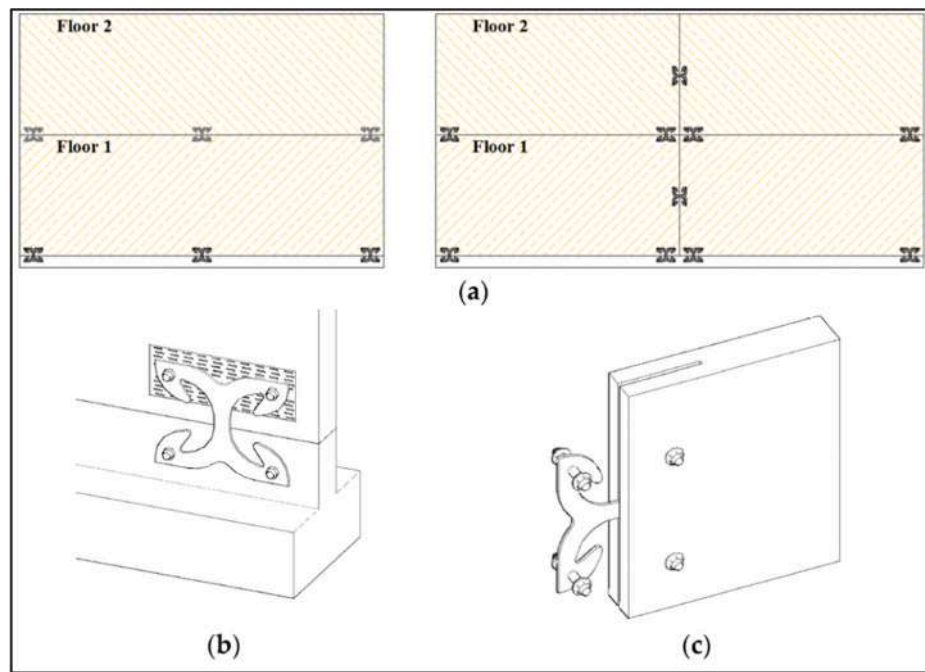


Fig. 11. CLT panels connections: (a) X-brackets, (b) panel-to foundation joint, and (c) panel to panel joint [128].

substantially with increased embedment length from 200 to 300 mm, while the increase in performance was less significant beyond 300 mm embedment length. It was also observed that the self-tapping screw reinforcement helped in reducing timber splitting and failure from the timber to the rod, and the performance in withdrawal capacity, shear stress, and stiffness increased substantially when two rods were used.

Werther et al. (2014) [146] examined the connections between primary and secondary beams using joist hangers with nails and screws, crosswise full-thread screws, and concealed aluminium dovetail connectors. It was noted that the use of screws is superior to the use of nails in joist hangers. Furthermore, 70 mm screw connections had lower temperatures and better embedding than 50 mm screw connections. However, the narrow beams with 100 mm width were not sufficient to maintain the amount of cross-section after 30 min of fire exposure.

The pull-out resistance of screws varies with loading rate, and the response of angle brackets and hold-downs may also be rate-dependent. However, experimental information on the dynamic response of these connectors remains limited. Consequently, numerical and analytical models often require assumptions that should be calibrated through targeted high-rate tests.

The research [147] analyzed hybrid screw-adhesive joints used in CLT-steel systems. It was stated that there was an increase in strength, stiffness, and ductility for the hybrid joints compared with other connections. The results obtained in this study were as follows: the strength of hybrid joints increased by 143% in relation to adhesive joints and 108% in comparison to screw joints.

In the study [148], the authors examined (analytical and numerical approaches) how orthogonal wall connections (OWC) affect the behavior of cross-laminated timber (CLT) shear wall structures. The findings showed that stronger OWC improved the building's lateral strength, stiffness, and energy dissipation, while moderate OWC strength provided the best ductility and overall seismic performance.

2.4. CLT fiber-retrofitting

Valdes et al. [149] have examined the flexural behavior of maritime pine CLT panels reinforced externally with natural flax fiber fabrics and bonded to the tension face of the CLT panels (Fig. 12). The results

showed that the ultimate loads of the three-layer CLT panels were improved by up to 73%, with noticeable improvements in stiffness, but no noticeable improvement was found in the five-layer CLT panels. The failure of the CLT panels was found to be brittle in tension, with no debonding of the reinforcement. The study concluded that the use of flax fiber reinforcement is highly beneficial for thin CLT members and is a promising sustainable solution.

In [150], Song et al. (2019) highlighted that adding CFRP plates to CLT greatly improved its structural performance (Fig. 13). The reinforced panels were 27% stiffer and 48% stronger in bending, and their bending capacity was 14% higher than regular 5-ply CLT, even though they were about 40% lighter.

Jung et al. (2020) [151] found that adding glass fiber to the connection zone of CLT walls (Fig. 14) improved their performance during seismic loading. While the monotonic horizontal shear strength did not change much, the reinforced walls had 38% higher residual strength, 18% higher yield strength, and a 38% greater ductility ratio compared to unreinforced walls. This shows that the reinforced walls were more resistant and stable under cyclic loads.

Lopez-Molina and Doudak [152] conducted experimental work to evaluate the effectiveness of retrofit methods for improving the blast resistance of cross-laminated timber (CLT) panels. In this study, two retrofit systems were evaluated: steel straps and glass fiber reinforced polymer (GFRP), see Fig. 15.

Steel straps were used to confine the timber panel horizontally, vertically, or in a combination of both to resist rolling shear failure. The steel strap retrofit resulted in improved post-peak response and ductility with little improvement in peak strength. On the contrary, the use of GFRP, which was externally applied to the timber panel using an epoxy resin, resulted in significant improvements in peak strength, stiffness, and ductility. The GFRP retrofit systems were applied to the timber panel in several configurations, including U-wrap reinforcement on the tension face, mid-span confinement layers, and wrapping along the entire length using fabrics with various fiber directions (0° , $0/90^\circ$, and $\pm 45^\circ$). The two retrofit systems resulted in improvements in panel stiffness by 10–28%, with the GFRP systems showing larger improvements in strength and ductility than the steel strap systems.

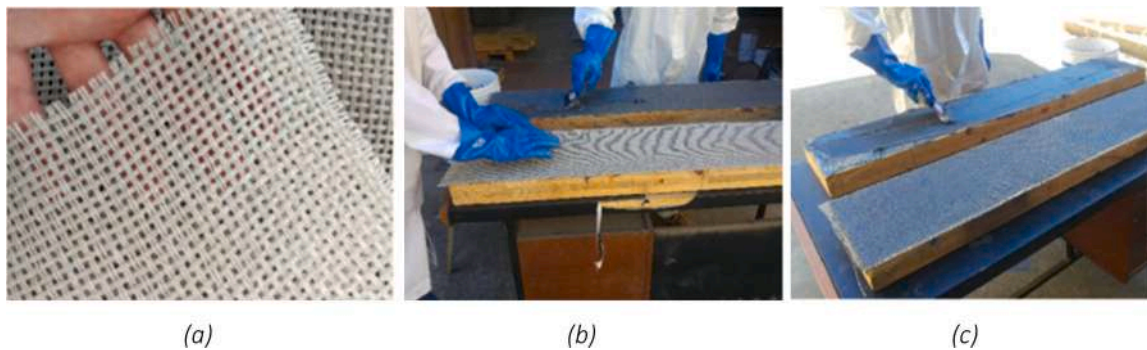


Fig. 12. Flax fiber CLT reinforcement: (a) flax fiber, (b) positioning on CLT, and (c) application of resin [149].

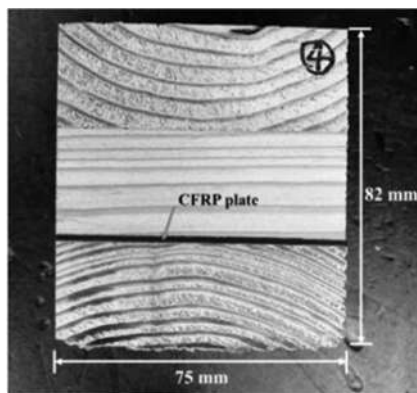


Fig. 13. CFRP plates added to the CLT specimen [150].

2.5. Experimental investigations on CLT under blast loading

Only limited full-scale blast-test data are available for CLT structures. Existing small-scale and component-level tests indicate partial delamination and localized failures, particularly near supports, where response is sensitive to manufacturing imperfections and boundary conditions.

Experimental results from field and shock tube tests indicate adhesive delamination to be the main failure mode for blast loading. Stress waves produce tensile and shear stress in adhesive joints, and once the bond strength is exceeded, delamination causes a loss of stiffness, increasing deflection, and a change in stress distribution.

Adding steel frames, composite overlays, or polyurea coatings can make the structure more ductile and help delay delamination. However, the quality of the bond and how long it lasts are still very important.

There is limited blast data available for CLTs, and differences in test specimen configuration, materials, adhesive systems, and boundary conditions make direct comparison of results difficult.

2.5.1. Shock tube tests

Shock tube testing has been employed to study the response of CLT to controlled blast-like loading pressures. In shock tube testing, it is possible to apply a number of repetitive loadings with a well-defined rise time. The outcome of shock tube tests has been found to include high variability of displacement, residual stiffness, and permanent deformation of nominally identical CLT specimens. It is believed that such variability is mostly due to material imperfections such as thickness variability of adhesive layers, voids in bond layers, fiber deviations, as well as moisture content of lamellas. It is clear that material imperfections affect stress wave propagation for CLT materials during high-rate loading, differently compared to homogeneous materials.

Côté, D. and Doudak, G. (2019) [93] investigated the performance of five types of connections for 5-ply CLT wall panels subjected to blast loads using a full-scale shock tube test (Fig. 16). End-grain screws and 60° double-threaded screws failed prematurely in brittle tension perpendicular to grain, preventing the panels from developing their flexural capacity. Conversely, the use of bearing-type connections, such as thin and thick steel angle brackets, allowed the CLT panels to reach the flexural capacity at the mid-span of the panel with less damage to the panel. Balloon construction was the best scenario, as it restrained the panel against rotation, which did not allow the connections to fail in a

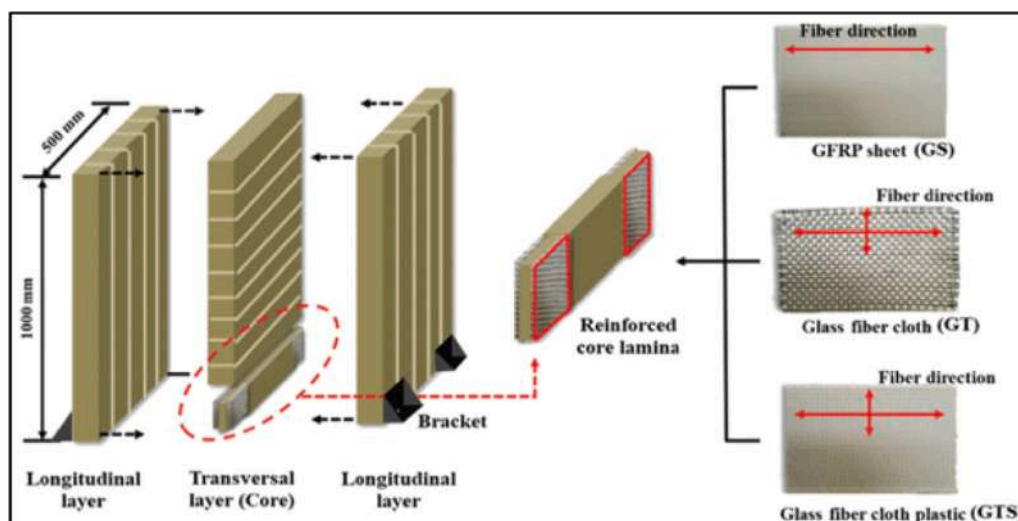


Fig. 14. Glass fiber CLT reinforcement [151].



Fig. 15. CLT specimens strengthened with (a) steel straps and (b) GFRP [152].

brittle manner.

Poulin et al. (2017) [37] conducted an experimental study on 3-ply (105 mm) and 5-ply (175 mm) CLT panels under static four-point bending and simulated blast loading using a shock tube test configuration. It was observed that the panels exhibited linear elastic behavior up to failure in flexure with 20% residual capacity after the peak resistance in the static test configuration. However, under dynamic loading, the panels exhibited an average DIF of 1.28 in terms of strength, while the stiffness was unchanged from the static test results. Two failure modes were observed: flexural failure similar to the static test results and rolling shear failure, which caused significant stiffness degradation (65–80%).

The research (Lopez-Molina, A. and Doudak, G. (2019) [152]) focused on the performance of 3- and 5-ply CLT panels retrofitted with steel straps in the horizontal and vertical directions and different configurations of GFRP systems (Fig. 17) under simulated blast loading by means of a shock tube. The results of the dynamic tests indicated that the

steel straps had minimal influence on the peak resistance of the structures but improved the post-peak resistance and ductility by reducing the rolling shear and debris. However, the use of the GFRP systems greatly improved the peak resistance, stiffness, ductility, and post-peak response, with the average increase in strength and ductility being 40% higher than that obtained by the steel straps.

Côté et al. (2018) [153] have performed dynamic tests on five-layer CLT wall panels. Panels were subjected to out-of-plane blast loads using a shock tube, taking into consideration realistic boundary connections such as end-grain screws, double-threaded screws at 60° , ductile steel angles, and stiff steel angles. The study showed that end-grain screws and double-threaded screws suffered from premature brittle tension perpendicular to grain failure, hence failing to attain their flexural capacities. The bearing-type angle connections performed much better than the end-grain screws and double-threaded screws, as ductile steel angles were able to dissipate blast energy through steel yielding and wood crushing, while stiff steel angles were able to attain ultimate flexural failure of the CLT panels.

2.5.2. Blast tank test

In [66], the blast tank tests (Fig. 18) examine the performance of



Fig. 18. Blast tank [66].

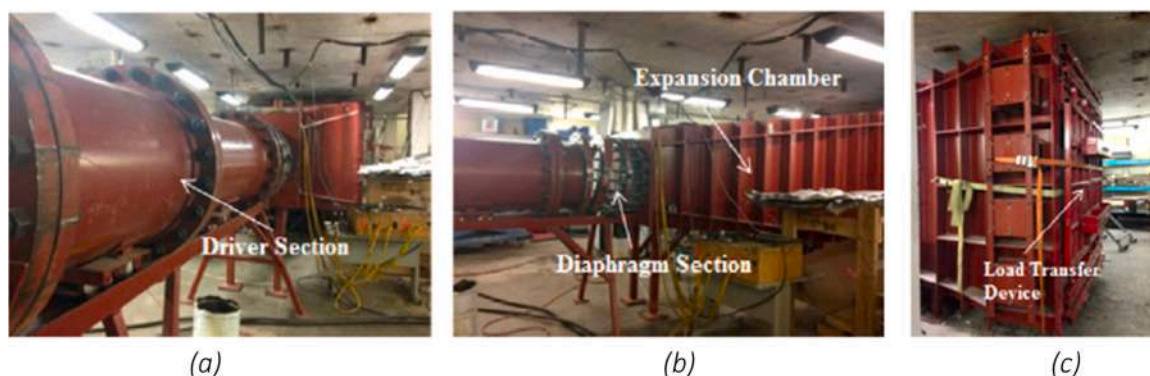


Fig. 16. Shock tube sections: (a) driver and diaphragm section, (b) expansion chamber, and (c) load transfer device [93].



Fig. 17. CLT retrofitted with man-made fibers, with various configurations: (a) Specimen 4, (b) Specimen 5, (c) Specimen 6, and Specimen 7 [152].

3-ply CLT panels under near-field blast loading through the use of live C4 explosives within a closed steel blast tank. The tests involved five trials with maximum peak incident pressures from 255 kPa to 797 kPa and incident impulse from 56.4 kPa-ms to 186.4 kPa-ms. The maximum displacement of the panels was found to be from 15.6 mm to 91.4 mm, with maximum peak support reaction being recorded as high as 114.5 kN. The response of the CLT panels mainly involved bending with predominant failure modes consisting of tension failure in finger joints and inherent wood defects.

2.5.3. Field blast tests

The available field tests indicate that loaded CLT structures can perform satisfactorily under blast loading, even when carrying simulated gravity loads representative of multi-story buildings. The panels were subjected to out-of-plane loading, simulating blast pressure on a wall, together with simultaneous axial in-plane loading, representing building weight. Laboratory tests showed that 3-ply panels resisted peak out-of-plane pressures of approximately 40–63 kPa, while 5-ply panels resisted substantially higher pressures of approximately 116–133 kPa [70].

The study included a sequence of full-scale explosive blast tests (field tests) on two-story CLT structures, beginning with Test 1, which was conducted on the same structures in an unloaded condition (without axial load) to establish a baseline response.

These specimens were subsequently repaired, subjected to loading to represent actual building loads, and tested once again with cylindrical TNT charges of approximately 30 kg and 90 kg, respectively, at a constant standoff distance of approximately 22.9 m. The following two loading regimes were used: Test 2, which was intended to maintain the specimen within its elastic limit, and Test 3, which was beyond the elastic limit to cause damage to the specimen. The results indicated that Test 1, corresponding to the unloaded condition, produced larger deflections, whereas Tests 2 and 3, with applied axial loads, remained stable and continued to carry their loads after blast exposure. Only minor exterior damage was observed, and no debris entered the interior [70].

Measurements of pressure aligned well with theoretical predictions, and deformations due to loads on the structure only varied by 10% from the unloaded case, and in some cases, the rebound deformations were even larger than the initial deformations due to loading. All results indicate that CLT structures behave predictably, whether under blast loads or not [70].

Finally, it is realized that secondary and environmental effects could significantly affect CLT blast resistance. Moisture content is known to affect the stiffness and strength of wood and adhesive bond-slip characteristics. Temperature and aging are known to affect adhesive bond strength and bond fracture characteristics. Existing defects like knots, cracks, and voids in the wood structure could serve as sites of stress concentrations under blast loading. Though mentioned briefly here and not being the subject of this paper by any means, they help explain the scatter of the experimental results.

In [66], the outdoor test (Fig. 19) investigates the dynamic response of 3-ply CLT panels under exposure to the C4 explosive load under near-field blast conditions.

During this test, a peak incident pressure of about 26.3 kPa, an incident impulse of 15.3 kPa-ms and positive phase duration of 1.73 ms was recorded. The CLT panel had a maximum deflection of around 17.1 mm while the peak support reaction was recorded to be around 38.9 kN. High speed photography revealed the formation of the shock-wave, the point of maximum deformation in the inbound direction, and the rebound response of the CLT panel. Flexural response was the primary mode of behavior for the CLT panel, with failure initiating from the tension face at finger joints and natural defects in the wood structure.

2.5.4. Statistics on the blast-load CLT systems research

A quantitative overview of the temporal evolution of research

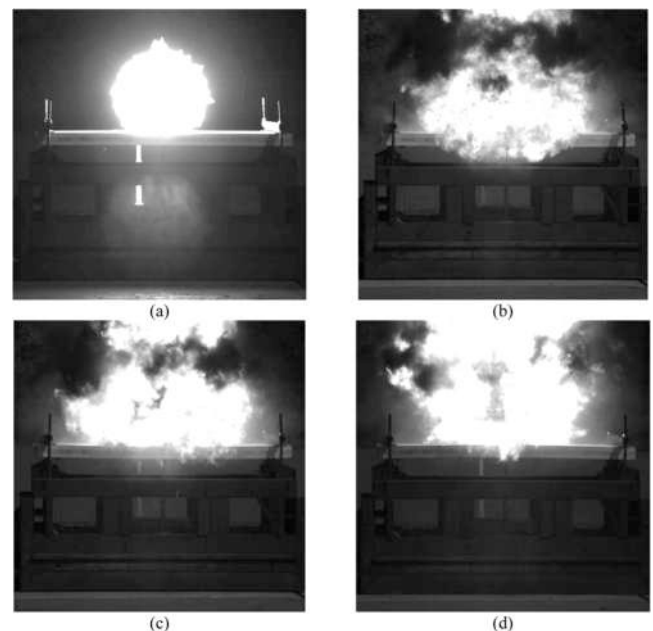


Fig. 19. Outdoor blast test, a time-lapse representation (a) detonation, (b) fully developed shockwave and fireball, (c) maximum inbound displacement, and (d) maximum rebound displacement [66].

activity related to blast-loaded CLT systems is presented in Fig. 20. It summarizes the number of publications identified in the literature together with their associated citation trends, providing an indication of both productivity and scientific impact over time. The bibliometric overview presented in Fig. 20 was developed through a targeted literature survey focused specifically on CLT structures subjected to blast or high-rate explosive loading conditions. The database was constructed by screening the references collected throughout this review together with additional searches performed using Scopus, Google Scholar and ScienceDirect. Only studies explicitly dealing with blast-loaded CLT panels, assemblies, or related analytical and numerical blast-response models were included. Duplicate entries, conference-paper extensions, and repeated citations referring to the same research work were removed to avoid overestimation of publication activity.

For each identified publication, the year of publication and the total citation count available at the time of manuscript preparation were recorded. Citation data were obtained primarily from Google Scholar and publisher indexing services. The final dataset was then grouped by publication year to determine both the annual number of publications and the corresponding cumulative citation counts. The histogram in Fig. 20 represents the number of publications per year, while the line plot illustrates the evolution of citations associated with these studies over time.

The results show that research on CLT under blast loading is a relatively recent field, with the first dedicated studies appearing around 2017, followed by a noticeable increase in publication activity between 2018 and 2020. The continued accumulation of citations in subsequent years suggests that these early contributions established the foundational knowledge base for subsequent analytical, experimental, and numerical investigations. Overall, the observed trend confirms that blast resistance of CLT structures remains an emerging research area characterized by limited but rapidly growing scientific output.

3. Design approaches and numerical modelling strategies

Finite Element (FE) modelling [154] has been considered and proposed for simulating CLT blast response. Abaqus and LS-DYNA software can incorporate rate-dependent material laws and cohesive zone models

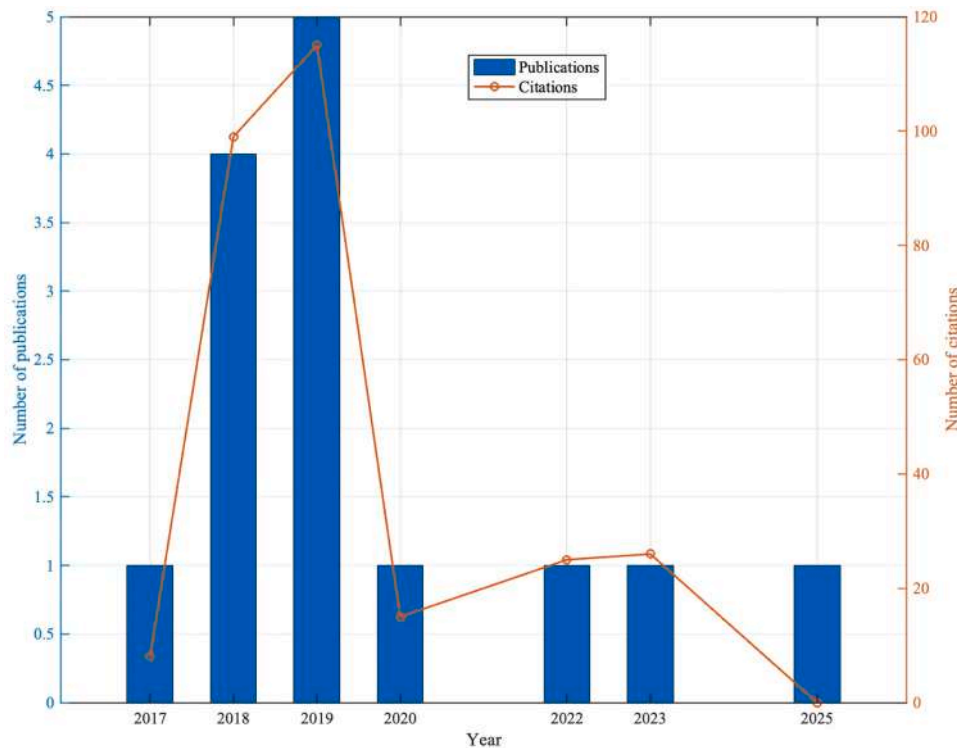


Fig. 20. CLT under blast loading: publications and citations per year.

(CZM) for delamination. Nevertheless, these simulations are computationally demanding and sensitive to input uncertainties.

Analytical models, particularly SDOF systems, offer simplified yet insightful tools for rapid response prediction. While well-established for reinforced concrete and steel beams [155], [156], equivalent formulations for CLT are lacking. The complexity arises from anisotropy, composite layering, and non-linear damping. Preliminary attempts have applied effective stiffness and mass formulations derived from modal analysis, but validation remains limited.

3.1. Semi-analytical model: SDOF/eSDOF/MDOF

Sanborn et al. (2018) [157] created a SDOF analytical model to predict how CLT structures respond to blasts. Their model uses the shear analogy method to find the effective bending stiffness of multilayer CLT panels, expressed as:

$$EI_{eff} = \sum_{i=1}^n E_i I_i = \sum_{i=1}^n E_i I_i \frac{h_i^3}{12} \quad (3)$$

where E_i , I_i , b_i , and h_i represent the modulus of elasticity, moment of inertia, width, and thickness of each lamina, respectively.

The model was applied to evaluate two-storey CLT structures subjected to TNT air-burst blasts. During the field tests, 32 lb (14.5 kg), 67 lb (30.4 kg), and 199 lb (90.3 kg) TNT charges were used and positioned 75 ft (22.86 m) from the structures.

Experimental results indicated that peak reflected pressures ranged from 5.05 psi (0.0348 MPa) to 13.2 psi (0.091 MPa), while reflected impulses reached a maximum of 65.7 psi-ms (0.453 MPa-ms).

The SDOF model predicted the maximum inward displacement of CLT wall panels, with errors typically within 13% of the measured field data. This shows the model matches well in the elastic response range. Under the highest loading condition, the measured displacement for V4 grade panels was approximately 4.57 in (11.61 cm), while the model predicted 3.44 in (8.73 cm). The discrepancy between measured and predicted values increased in the presence of plastic deformation and

lamina fracture. The study concluded that CLT structures primarily exhibit elastic behavior under moderate blast loads and that the SDOF approach serves as a useful preliminary tool for blast analysis.

Doudak et al. (2022) [158] have proposed methodologies for timber members (including light-frame wood stud walls, glulam members, and CLT) panels subjected to blast loading. The proposed design method evaluates the peak resistance of CLT panels using

$$R_{peak} = \min(2V_{r-D}, \frac{8M_{r-D}}{L}) \quad (4)$$

where V_{r-D} and M_{r-D} are the dynamic shear and bending resistances, respectively, and L is the panel span.

The methodology considers parameters such as dynamic increase factors (DIF), strength increase factors (SIF), and ductility ratios obtained from experimental tests. The experimental results from static and dynamic tests indicate a dynamic increase factor of 1.2–1.3 for CLT flexural strength and a DIF of 1.2 for rolling shear. The results show an SIF of 2.0 for rolling shear strength. The SDOF-based approach was validated with 89 blast tests and accurately predicted how structures respond to blasts. The average ratio was 0.99, with a coefficient of variation of 20%. The results also indicate that the new design method for CLT peak resistance has an average ratio of 1.01 (COV $\approx$ 8%), showing high accuracy in predicting experimental results. The results also indicate that existing blast design provisions may overestimate CLT resistance because they do not consider rolling shear failure mechanisms. The results emphasize the importance of developing new design procedures to improve blast-resistant timber structures.

Oliveira et al. (2023) [79] studied how glued-laminated timber (glulam) beams and CLT panels respond to repeated blast loads. They used a shock-tube testing facility and modeled the structural response using an equivalent SDOF (eSDOF) dynamic model

$$k_{LM} \ddot{m} \ddot{u}(t) + R(u, t) = P(t)A \quad (5)$$

where k_{LM} is the load-mass transformation factor, m is the system mass, $R(u, t)$ is the resistance function, $P(t)$ is the reflected blast pressure, and

Ais the loaded area. The peak structural resistance for flexural failure was calculated using

$$R_{peak} = \frac{8M_{r-D}}{L} \quad (6)$$

where, M_{r-D} is the dynamic bending resistance and L is the member span. The study conducted 12 shock-tube blast tests on six specimens (three glulam and three CLT members) under dynamic four-point bending. Experimental results showed that glulam members exhibited nearly linear-elastic behavior until flexural failure, with an average dynamic peak resistance of 67.8 kN and modulus of rupture of 55.6 MPa.

In comparison, CLT panels had resistance curves that looked like steps because of the gradual failure of the longitudinal laminates and rolling shear in the transverse layers. Their average peak resistance was 178.1 kN, and their dynamic rolling shear strength was about 1.4 MPa. The study also found that minor cracks in glulam members during earlier blasts did not greatly affect their stiffness or strength. However, CLT panels lost stiffness over time because of rolling shear damage from repeated loading. The proposed eSOF modeling approach, which includes stiffness degradation by reducing secant stiffness, was able to track damage buildup and predict mid-span displacement accurately. This shows it can be used to assess timber members after multiple blasts and for post-blast structural evaluation.

The study by Viau and Doudak (2019) [159] investigated the blast behavior of 5-ply CLT panels with realistic boundary connections using full-scale experiments and a two-degree-of-freedom numerical model. The MDOF model separately represented the CLT panel and the end connections, and was governed by a coupled system of equations of motion, expressed in matrix form as:

$$\begin{Bmatrix} m_c & 0 \\ 0 & k_{LM}m_p \end{Bmatrix} \begin{Bmatrix} \ddot{u}_c \\ \ddot{u}_p \end{Bmatrix} + \begin{Bmatrix} R_c \\ R_p - R_c \end{Bmatrix} = \begin{Bmatrix} 0 \\ F \end{Bmatrix} \quad (6)$$

where m_c and m_p are the masses of the connections and panel, R_c and R_p are the connection and panel resistances, k_{LM} is the load-mass transformation factor, and F is the applied blast force.

Experimental results showed that the ML24Z angle connections exhibited a DIF of 1.55, while thicker steel angle connections showed no significant DIF. The simply supported CLT panels showed a DIF of 1.31 on maximum resistance, and the validated MDOF model predicted the maximum displacement with an average ratio of 0.996 (COV = 0.02), confirming the importance of connection behavior in the blast response of CLT assemblies.

3.2. Numerical model: FEM

Saloo & Viau (2025) [160] proposed a FE modeling technique to study the response of CLT panels to contact charge detonation and near-field blast loads. The numerical simulations were conducted with an explicit dynamic analysis using LS-DYNA, with inputs for blast pressure in the form of LOAD BLAST ENHANCED (LBE) scheme and Kingery-Bulmash equations for blast pressure. The mechanical behavior of CLT was represented using the MAT-143 wood material model, which incorporates a reduced form of the Modified Hashin failure criteria to capture tensile, compressive, and shear failures in both parallel and perpendicular grain directions. The failure functions were defined as

$$f_{||} = \frac{\sigma_L^2}{X_{||}^2} + \frac{\sigma_{LT}^2 + \sigma_{LR}^2}{S_{||}^2} - 1 \quad (7)$$

$$f_{\perp} = \frac{(\sigma_R + \sigma_T)^2}{Y_{\perp}^2} + \frac{\sigma_{RT}^2 + \sigma_{R\sigma_T}}{S_{\perp}^2} - 1 \quad (8)$$

where σ_L , σ_R , and σ_T represent stresses in the longitudinal, radial, and tangential directions, while X , Y , and S denote the tensile/compressive

and shear strengths of wood in the corresponding directions. The model was tested using experiments on 3, 5, and 7-ply CLT panels exposed to C4 explosive charges. It predicted the mid-span displacement at failure with an average error of about 9.9% (COV = 16.5%). The model predicted different failure modes, such as flexural failure from near-field blasts and breaching from contact charges. However, LBE may not give accurate results for thicker panels under contact detonations, so a more precise method like ALE modeling is needed.

Shahnewaz et al., 2017 [161] used a validated finite element model to investigate the seismic response of CLT shear walls equipped with different connections. The findings showed that the increase in the number of connectors from 4 to 7 resulted in an increase in the lateral load-carrying capacity by 53–57% and stiffness by 33–39%, highlighting the significance of connectors in seismic design.

The results of numerical analysis on a historical masonry church have shown (on Longarini et al. (2020) [162]) that the introduction of the CLT diaphragm, along with optimized steel connections, improves the seismic response of historical masonry churches. The explicit modeling of the connections reduces the in-plane shear force of the CLT panels by 20–25% in linear analysis and 35% in nonlinear analysis, as compared to the models without the representation of the connections. A slight increase in the drift value, i.e., 10%, is also noted, but the stresses remain within the acceptable range. The nonlinear analysis results show that the plasticization of the connections allows for the redistribution of the stresses, thus providing the required dissipation of the ductility capacity. The optimized design of the CLT diaphragm is effective for the control of the rocking motion of the walls, and the thickness design of the panels is also optimized.

3.3. Reliability model

Swinea et al. (2025) [163] evaluated the ballistic resistance of CLT panels using a reliability-based First-Order Second-Moment (FOSM) method combined with a physics-based empirical penetration model. The depth of penetration (DOP) was estimated using

$$DOP = C_1 \left(\frac{v^a \omega^b}{\left(\frac{\pi D^2}{4} \right)^c H^d} \right) \quad (9)$$

where v is projectile velocity (m/s), ω is projectile mass (kg), ρ is wood density (kg/m³), D is projectile diameter (m), and H is Janka hardness (N). The method was validated using 61 ballistic impact tests for Douglas Fir CLT panels using a 12.7 mm steel sphere projectile and the existing CLT ballistic databases. The results showed that the FOSM method can accurately predict the penetration depth distribution and that all the test data were within the 95% confidence intervals of the predictions. The study concluded that the main variable controlling the uncertainty in ballistic resistance is the material variability in density and hardness, and that density-based grouping reduces the scatter in the predictions for CLT design in force protection applications.

Further research should also address material-level constitutive modeling and blast-simulation strategies for CLT, drawing where appropriate on approaches already used for steel and reinforced concrete structures [164–167].

3.4. Comparative assessment of available modelling approaches

A comparative evaluation of the available modelling approaches highlights significant differences in predictive capability, computational efficiency, and suitability for engineering design. Although simplified analytical, numerical, and reliability-based models are all capable of representing aspects of the blast response of CLT structures, their applicability depends strongly on the required level of accuracy and the physical phenomena of interest.

Simplified analytical approaches based on equivalent SDOF formulations provide an efficient means of estimating global structural response, particularly maximum displacement and support reactions. These models are widely used in blast engineering because they allow rapid prediction of structural demand using limited computational resources. Their primary advantage lies in their simplicity and suitability for preliminary design and parametric studies. However, classical SDOF formulations rely on equivalent stiffness and resistance parameters and are therefore limited in their ability to capture localized damage mechanisms such as rolling shear, delamination, or connection failure. In addition, their predictive capability depends strongly on the accuracy of transformation factors and resistance functions, which must be calibrated against experimental data.

Enhanced analytical approaches, including eSDOF and MDOF formulations, provide improved representation of structural behavior by explicitly accounting for stiffness degradation, connection flexibility, and interaction between structural components. Compared with classical SDOF models, these approaches offer greater accuracy in predicting displacement histories and failure progression. MDOF formulations are particularly advantageous when connection behavior governs the global response, as is frequently the case in CLT systems subjected to blast loading. Nevertheless, the increased modelling complexity and parameter definition requirements limit their use in routine design applications without adequate experimental calibration.

FEM represent the most comprehensive modelling framework for simulating blast-loaded CLT structures. These models allow detailed representation of orthotropic material behavior, strain-rate effects, cohesive-zone modelling of adhesive interfaces, and progressive failure mechanisms. As a result, FEM approaches are capable of reproducing complex phenomena such as interlayer delamination, rolling shear, and localized crushing. However, their predictive reliability depends strongly on the availability of validated material models and accurate boundary-condition definitions. In addition, the computational cost associated with high-fidelity simulations makes FEM approaches more suitable for advanced research investigations, validation studies, and design verification rather than preliminary structural assessment.

Reliability-based approaches introduce a probabilistic framework that explicitly accounts for uncertainty in material properties, loading conditions, and model parameters. These methods provide valuable insight into the variability of structural response and enable the estimation of failure probability under extreme loading conditions.

Although reliability-based methods are not typically used for direct structural response prediction, they play an important role in risk assessment and performance-based design. Their implementation, however, requires statistically representative datasets that remain limited for CLT blast applications.

From an engineering perspective, the comparison among modelling approaches suggests that no single method is universally sufficient for predicting the blast response of CLT structures. Instead, a hierarchical modelling strategy is recommended, in which simplified analytical models are used for preliminary response estimation, enhanced analytical or MDOF models are adopted for refined component-level analysis, and finite element simulations are employed for detailed investigation of local failure mechanisms. Reliability-based methods can then be integrated to quantify uncertainty and support performance-based design frameworks.

The available modelling approaches can be interpreted as forming a hierarchical framework of increasing complexity and predictive capability, see Fig. 21. This hierarchical structure suggests that integrated modelling workflows—beginning with simplified analytical screening and progressing toward advanced numerical simulation—represent the most efficient strategy for evaluating blast resistance in CLT systems.

Overall, the comparative assessment indicates that future research should focus on developing integrated modelling frameworks that combine the efficiency of simplified analytical methods with the predictive accuracy of high-fidelity numerical models, supported by systematic experimental validation. Such an approach will improve the reliability of blast-resistant design methodologies and facilitate the practical implementation of CLT structures in applications requiring resistance to extreme loading conditions.

Table 10 presents a critical comparison of the principal modeling approaches applied to CLT. Reduced-order SDOF and TDOF models offer a computational-efficient approach to estimate the global response of CLT panels subjected to blast loadings and account for rolling-shear and connection effects if properly formulated and calibrated. However, the simplification of the model does not allow representing the damage mechanisms on a local scale, which is possible in case of the multiscale models, accounting for cohesive-zone models (CZM), allowing detailed representation of rolling-shear cracking and interaction between different failure modes at the same time. It should be noted that reduced-order models are already validated in relation to simulated blasts, but the multiscale and CZM models considered in this chapter are mostly

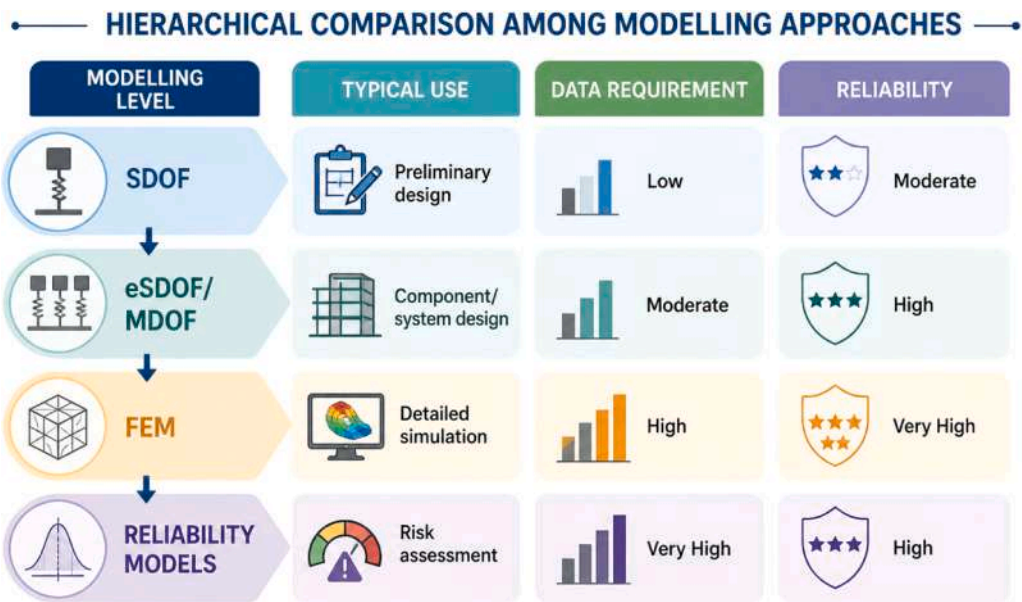


Fig. 21. Comparison among modelling strategies.

Table 10

Critical comparison of modelling approaches applied specifically to CLT.

Modelling approach	CLT-specific application	Main advantages	Limitations / challenges for blast and high-rate CLT	Validation for CLT	Ref.
Single-degree-of-freedom (SDOF) modelling	CLT panels are transformed into an equivalent SDOF system using resistance functions and transformation parameters. Poulin et al. developed CLT resistance models incorporating experimentally observed high strain-rate effects, flexural and rolling-shear failure, and post-peak residual resistance.	Computationally efficient and suitable for predicting global panel response, particularly maximum displacement and displacement–time histories. Well suited to preliminary blast assessment and design-oriented analysis.	Does not explicitly resolve three-dimensional local damage, crack propagation, delamination or detailed connection behaviour. Accuracy depends on representative resistance functions and correct identification of the governing failure mode. The authors noted that further testing and more advanced modelling are required to generalize the results.	Direct simulated-blast validation. Predicted displacements agreed reasonably with experimental results; after accounting for flexural and rolling-shear failure, maximum displacement was underpredicted by about 3% on average.	Poulin et al. (2018) [37]
Design-oriented SDOF methodology incorporating rolling shear	Design methodologies for blast-loaded CLT panels use SDOF analysis with member-specific resistance curves, dynamic parameters and design modification factors. Rolling-shear and flexural failure are incorporated in the CLT resistance formulation.	Provides a practical engineering design procedure while retaining important CLT-specific failure mechanisms. Considerably less computationally demanding than detailed FE modelling and suitable for design calculations.	Relies on idealized resistance curves and experimentally/ design-derived parameters. The CLT response showed greater variability than some other timber systems because sudden ply failures cause abrupt changes in resistance. Applicability is primarily to far-field blast conditions and configurations represented by the available test data.	Direct verification against published full-scale blast tests. The overall SDOF methodology produced an average predicted-to-experimental displacement ratio of 0.99, with a COV of 20%.	Doudak et al. (2022) [158]
TDof panel–connection modelling with rate-dependent connection behaviour	The CLT panel and boundary connections are represented as interacting degrees of freedom. Component-level connection behaviour is incorporated into full-scale assembly models. Viau and Doudak investigated two angle-type CLT connections using static, component-level and simulated-blast testing.	Explicitly represents panel–connection interaction, connection deformation, axial restraint and connection-specific failure mechanisms. More realistic than idealized simply-supported SDOF models where connection flexibility substantially affects system response.	Requires reliable component-level resistance data for both the CLT panel and its connections. Connection response and rate enhancement are strongly failure-mode dependent, and axial restraint can significantly influence deformable connections.	Direct static and simulated-blast validation. The developed two-degree-of-freedom model reproduced assembly response with reasonable accuracy and predicted both displacement and governing failure mode when suitable inputs were used.	Viau & Doudak (2019) [159]
Realistic boundary-connection representation	Full-scale CLT wall panels with realistic wall-to-floor/ end connections were investigated instead of assuming idealized simply-supported boundaries. Connection configurations included end-grain screws, angled screws, thin and thick steel angles and balloon-type restraint.	Demonstrates the major influence of boundary detailing on global CLT blast behaviour, including rotational restraint, energy dissipation and premature connection failure. Provides experimental basis for connection-inclusive analytical models.	Primarily an experimental system-level approach rather than an independent numerical modelling method. Performance is highly connection-specific, so conclusions cannot automatically be generalized to other connection types.	Direct full-scale simulated-blast evidence. Thirteen CLT walls with different connection details were tested. Simplified idealized simply-supported models were found inadequate for reproducing the full system behaviour.	Côté & Doudak (2019) [168]
Multiscale homogenisation + cohesive-zone modelling (CZM)	Four spatial scales—from the wood cell wall, fibres and growth rings to the structural CLT plate—are linked through sequential homogenisation. Cohesive interfaces at the macroscopic scale reproduce inter-fibre rolling-shear cracking and interlaminar delamination, while domain decomposition is used to solve the large FE system.	Connects micro-/material-scale characteristics with panel-scale structural behaviour. Explicitly represents progressive rolling-shear cracking and delamination and allows investigation of effects such as wood density, edge-gluing and span-to-depth ratio.	Computationally demanding and highly dependent on fracture/cohesive parameters. For the investigated radiata pine and adhesive, several fracture parameters were unavailable and were therefore adopted from other wood species or composite-laminate studies and adjusted to reproduce experimental behaviour. The model does not include high-strain-rate constitutive behaviour and was not validated for blast loading.	Direct quasi-static CLT validation for rolling-shear failure. Numerical predictions were compared successfully with experimental CLT results, but validation was not blast-specific.	Saavedra Flores et al. (2016) [169]
Multiscale LaTIn domain decomposition + CZM	A CLT-specific multiscale domain-decomposition framework employs cohesive interfaces to model interlaminar and intralaminar damage, including rolling shear,	Captures interaction between several CLT failure mechanisms while reducing the computational burden through optimized domain partitioning and parallel computation. The proposed	Requires detailed cohesive parameters, appropriate interface placement and a relatively sophisticated computational framework. Fully nonlinear simulations can remain computationally	Direct experimental CLT validation for rolling-shear failure. Experimental comparisons confirmed accurate prediction of rolling-shear failure, but no	Fernández et al. (2026) [170]

(continued on next page)

Table 10 (continued)

Modelling approach	CLT-specific application	Main advantages	Limitations / challenges for blast and high-rate CLT	Validation for CLT	Ref.
	transverse cracking, delamination and bending-related failure.	strategy reduced degrees of freedom by up to 55%, subdomains by up to 70%, and the number of iterations by about 70%.	expensive; one reported case required about 7.8 h. The framework was developed for quasi-static out-of-plane rolling-shear response, so applicability to blast/high-rate loading remains unverified.	blast/high-strain-rate validation was reported.	

validated under quasi-static loadings. Thus, accounting for strain rate dependent behavior and connection failure in detailed CLT models and validating them under blast and impact loadings is another important future research direction.

3.5. Practical implications for blast-resistant design

The reviewed experimental evidence has important implications for the design of CLT structures subjected to blast and impact loading. In Eurocode 5 (EC5), the modification factor (k_{mod}) accounts for the effects of load duration and moisture conditions on timber strength [171]. However, although EC5 includes an instantaneous load-duration class, its conventional load-duration framework was not specifically developed to represent the high strain rates associated with blast and impact events [171]. Consequently, direct extrapolation of the existing k_{mod} values to such extreme loading conditions should be treated with caution [100,172,173].

Experimental studies indicate that timber and engineered timber products may exhibit increased resistance under high-rate loading [100,172,173]. In particular, simulation experiments on CLT panels revealed an average DIF of about 1.28 kN, whereas no proportional increase in initial stiffness was observed [37]. The same investigation also demonstrated that dynamic loading can influence the governing failure mechanisms, including rolling-shear damage and considerable post-damage stiffness degradation [37]. These observations suggest that a single load-duration modification factor may not adequately represent all aspects of the dynamic response of CLT [31,37]. Therefore, the available evidence suggests that the conventional EC5- k_{mod} formulation alone may not fully capture CLT behavior under blast and impact loading and that explicit strain-rate-dependent modifications, such as a DIF for resistance, may merit consideration in future design provisions [31,37,174]. Nevertheless, the existing experimental database remains insufficient to establish generally applicable strain-rate-dependent factors, particularly across different CLT lay-ups, timber grades, loading directions, rolling-shear behavior, connection details, and failure modes [174]. Furthermore, the reported increase in resistance without a corresponding increase in initial stiffness indicates that strength and stiffness should not necessarily be assigned the same rate-dependent modification. Additional systematic experimental investigations covering relevant strain-rate regimes are therefore required before reliable strain-rate-dependent modification factors can be incorporated into European design provisions for CLT structures subjected to blast and impact loading [103].

From a practical design perspective, several additional issues should also be considered. High-rate behavior of CLT cannot be assessed solely through rate-dependent properties of the constituent timber, because the global response is strongly influenced by panel layup, rolling-shear behavior of transverse layers, adhesive interfaces and possible delamination. Dynamic load redistribution, inertia effects, stress-wave propagation and localized failure around impact zones further limit the applicability of static design assumptions. Membrane and two-way action should not automatically be included as beneficial resistance because at large displacements, tensile membrane or catenary action would additionally require adequate in-plane restraint and substantial

tensile and rotational capacity in the panel-to-panel and panel-to-support connections. Progressive-collapse studies of CLT floors indeed show that catenary action can become an important alternative load path, but its effectiveness is highly dependent on connection strength and ductility [175].

4. Summary of knowledge gaps

The review of the available literature demonstrates that, despite significant progress in the understanding of CLT behavior under dynamic loading, substantial knowledge gaps remain in the context of blast-resistant design. The temporal distribution of the available studies, summarized in Fig. 20, clearly indicates that research activity on CLT structures subjected to blast loading is relatively recent and remains limited in volume compared with other structural materials such as reinforced concrete and steel. Although the number of publications has increased progressively since 2017, the overall body of experimental and modelling evidence remains insufficient to support fully validated design-oriented methodologies. These gaps are primarily associated with limitations in experimental evidence, modelling capabilities, material characterization, and design-oriented implementation frameworks.

4.1. Experimental and material-level gaps

A major limitation in current research is the lack of comprehensive experimental datasets capable of capturing the full range of failure mechanisms in CLT structures subjected to varying blast intensities. Most available studies are limited to small-scale specimens or specific configurations, resulting in fragmented datasets that restrict the generalization of findings. In particular, boundary conditions and connection behavior remain insufficiently characterized under impulsive loading, despite their critical role in governing structural response.

Another unresolved issue concerns the absence of standardized dynamic material models capable of representing strain-rate effects in orthotropic timber and adhesive interfaces. The layered nature of CLT introduces complex interactions between lamellae and bonding layers, especially under high strain-rate conditions. The behavior of adhesives and interlayer bonding under blast loading remains poorly quantified, leading to uncertainties in predicting delamination and progressive failure.

Furthermore, inadequate consideration of layered material behavior - including adhesive response under rapid loading - and the influence of boundary constraints significantly limits the predictive accuracy of current structural models. These aspects are particularly important in blast scenarios, where localized stress concentrations and interlayer interactions strongly influence global structural response.

4.2. Modelling and numerical framework gaps

Although several modelling approaches have been proposed, limited efforts have been made to develop simplified analytical frameworks specifically tailored to CLT systems and validated against robust experimental evidence. Existing SDOF-based formulations, widely

adopted in conventional materials such as reinforced concrete and steel, require adaptation to account for anisotropic stiffness distribution, rolling shear mechanisms, and connection flexibility.

In addition, there is a need for improved validation strategies capable of linking experimental observations, analytical predictions, and numerical simulations within a unified modelling framework. At present, many numerical studies rely on assumptions that are not systematically validated due to the limited availability of reliable experimental benchmarks.

Another important limitation lies in the lack of design-oriented tools capable of enabling rapid structural assessment and supporting resilience-based design strategies. The absence of simplified yet reliable predictive methods restricts the practical adoption of blast-resistant design methodologies in engineering practice.

4.3. Structural design and system-level gaps

At the structural level, limited attention has been given to the development of protective and retrofitting strategies specifically tailored to CLT systems. Although several strengthening approaches have been investigated, systematic evaluation of their effectiveness under blast loading remains incomplete.

In addition, there is limited information available regarding post-blast damage assessment, residual capacity evaluation, and repairability of CLT structures. These aspects are essential for defining performance-based design criteria and ensuring structural resilience following extreme events.

Finally, the lack of standardized design recommendations for performance-based blast-resistant CLT structures remains one of the most critical barriers to widespread engineering implementation. The absence of unified guidelines restricts the translation of research findings into practical design methodologies.

4.4. Implications for future model development

The identified knowledge gaps strongly support the development of simplified yet reliable analytical models capable of predicting the dynamic response of CLT beams and panels subjected to blast loading. Such models should aim to capture the essential nonlinear behavior of layered timber systems while maintaining computational efficiency suitable for engineering applications.

Future modelling developments should therefore focus on:

1. Development of effective stiffness, damping, and resistance parameters capable of representing the nonlinear and anisotropic behavior of CLT structural components.
2. Systematic calibration of analytical formulations using validated experimental and numerical data to ensure predictive reliability.
3. Verification of model predictions using displacement histories, failure modes, and damage patterns obtained from controlled blast experiments.

4.5. Strategic research outlook

Addressing the identified knowledge gaps requires coordinated research efforts combining experimental, analytical, and numerical approaches. In particular, future investigations should prioritize:

- Large-scale experimental campaigns covering realistic boundary conditions
- Development of validated material constitutive models
- Integration of multi-scale modelling strategies
- Implementation of probabilistic frameworks for uncertainty quantification

The systematic resolution of these challenges will significantly

enhance the predictive reliability of blast-resistant design methodologies and support the safe and resilient implementation of CLT structures in applications exposed to extreme loading conditions.

5. Conclusions

The state-of-the-art review demonstrates that while CLT has established itself as a sustainable alternative to conventional materials, its behavior under blast loading is still insufficiently characterized. The reviewed studies reveal that delamination, adhesive failure, and boundary effects dominate the failure response, and that high-fidelity numerical models, although insightful, remain limited by uncertainties in material properties, connection behavior, and boundary conditions, which restrict their direct applicability to engineering design.

The bibliometric trend presented in Fig. 20 further confirms that the scientific development of blast-resistant CLT systems is still in its early stages, highlighting the urgent need for coordinated experimental programs and validated modelling strategies. A critical outcome of this review is the recognition that the current body of experimental evidence remains insufficient to fully describe the complex multi-layered response of CLT under high strain-rate loading. Existing experimental campaigns are limited in number, often restricted to component-level tests, and characterized by significant variability arising from differences in material properties, manufacturing processes, adhesive systems, and connection details. Consequently, the development of reliable predictive tools cannot progress without the generation of new, high-quality experimental datasets specifically designed to capture failure mechanisms, strain-rate effects, and system-level interactions.

Therefore, simplified analytical tools are needed to predict blast-induced deflections and failure thresholds in CLT members. However, the reliability of such tools fundamentally depends on rigorous experimental validation. Future work should therefore focus not only on analytical and numerical developments but also on the systematic execution of new experimental programs, including both small-scale controlled tests and large-scale structural investigations.

Future research should aim to provide:

- A calibrated SDOF model for CLT beams and panels subjected to blast loading, supported by validated transformation factors and resistance functions.
- A comprehensive experimental database covering different layouts, connection configurations, boundary conditions, and loading regimes.
- New experimental campaigns specifically addressing connection behavior, bond-line performance, and progressive failure mechanisms under impulsive loading.
- Full-scale or sub-assembly blast tests capable of capturing realistic structural interactions and validating simplified predictive methods.
- Recommendations for incorporating experimentally validated analytical tools into resilience-oriented design frameworks.
- Identification of priorities for coordinated international testing campaigns and joint research initiatives within collaborative networks such as COST Actions.

Ultimately, the advancement of blast-resistant design for CLT structures relies on the integration of experimental observations, analytical formulations, and numerical simulations within a unified framework. The systematic generation of new experimental data will play a decisive role in reducing uncertainties, improving model reliability, and enabling the development of performance-based design methodologies tailored to mass timber systems.

These developments would contribute not only to scientific advancement but also to the safe and confident adoption of CLT structures in applications where resistance to extreme loading scenarios is required, thereby strengthening collaboration between research institutions and expanding global expertise in blast-resistant timber engineering.

CRediT authorship contribution statement

Flavio Stochino: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Mislav Stepinac:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization. **Arnas Majumder:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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