buildings

MDPI

Systematic Review

Innovative Practices for CLT Buildings Towards Embodied Carbon Reduction in Seismic Zones: A Systematic Review

Victor Rosales [1,2,3], Carmen Avilés-Palacios [4,*], Sergio Álvarez [5] and Emilio Luengo [6]

1 ETSI Montes, Forestal y del Medio Natural, Universidad Politécnica de Madrid (UPM), c/ José Antonio Novais 10, 28040 Madrid, Spain; victor.rosales@alumnos.upm.es
2 Department of Construction Sciences, Facultad de Arquitectura, Universidad del Bío-Bío, Concepción 4051381, Chile
3 National Excellence Center for Timber Industry (CENAMAD), Pontifical Catholic University of Chile, Santiago 8320165, Chile
4 Departamento Ingeniería de Organización, Administración de Empresas y Estadística, ETSI Montes, Forestal y del Medio Natural, Universidad Politécnica de Madrid (UPM), c/ José Antonio Novais 10, 28040 Madrid, Spain
5 Department of Land Morphology and Engineering, Universidad Politécnica de Madrid, 28040 Madrid, Spain; sergio.alvarez@upm.es
6 Escuela de Ingeniería de Fuenlabrada, Universidad Rey Juan Carlos (URJC), 28942 Fuenlabrada (Madrid), Spain; emilio.luengo@urjc.es
* Correspondence: carmen.aviles@upm.es; Tel.:+34-910671632

Abstract

The use of Cross-Laminated Timber (CLT) panels in buildings offers earthquake resistance with a low carbon footprint. However, significant seismic displacements can cause damage, raising concerns about the long-term embodied carbon balance obtained, particularly if significant interventions are required to restore the original functionality. This study embraces a systematic review of innovations considered for massive timber structures in seismic zones, focusing on embodied carbon emission reduction. The analysis undertaken is based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) using the Scopus and Web of Science database references published from 2010 to 2025. A total of 53 documents meeting the search criteria were identified and assessed, considering their degree of technological maturity (TRLs). The results highlight efforts toward innovation in the performance of connections and lateral stabilization to minimize damage and enhance reparability, revealing the need to link new practices and technologies to the structural and environmental results of the solution, particularly in terms of efficiency in the use of materials about their possible repair and reuse at different stages of the life cycle. The availability of innovations aimed at carbon footprint reduction, and which present a high degree of technological maturity is reviewed and the potential of these solutions is evidenced in places where seismic vulnerability greatly influences the design; combining performance with the aim of achieving a carbon-neutral economy.

Keywords: low carbon; seismic; resilience; green building; innovation; CLT building

check for updates

Received: 15 October 2025
Revised: 6 November 2025
Accepted: 8 November 2025
Published: 17 November 2025

Citation: Rosales, V.; Avilés-Palacios, C.; Álvarez, S.; Luengo, E. Innovative Practices for CLT Buildings Towards Embodied Carbon Reduction in Seismic Zones: A Systematic Review. *Buildings* **2025**, *15*, 4141. https://doi.org/10.3390/buildings15224141

1. Introduction

The construction industry is facing increasing pressure to improve its sustainability practices, with a growing need to reduce environmental impact [1]. The building sector must integrate green infrastructure through the adoption of sustainable building practices [2], particularly given international commitments such as the Paris Agreement aimed at net-zero carbon emissions [3]. However, the technological process has not been up to the task of reaching the targets [4].

In areas of high seismic vulnerability, innovations should be oriented towards recyclability and the life cycle efficiency of 'long-term' products in terms of carbon sequestration [5]. Hasani & Riggio [6] highlight the importance of incorporating adaptable design strategies early in the decision-making process, this being in the group "Cradle to Grave strategies" according to Fang et al. [7]. Furthermore, the 4 R paradigm (reduce, reuse, recycle, and recovery) is fundamental to the circular economy, originating from initial sustainability efforts focused on waste reduction and resource conservation. Among the latter, reuse implies prolonging the lifespan of materials through repurposing while recycling entails transforming and valuating waste [8].

Ugalde et al. [9] state that timber design for areas of high seismic vulnerability should not only be further improved but also linked with carbon sequestration practices. The design of multi-story timber buildings located in such areas requires the adoption of strategies as regards the selection of the structural system, damage tolerance [10,11], selection of materials and connectors [12,13], as well as of secondary elements [14–16], incorporating carbon footprint as an important variable [17,18]. However, to date previous reviews have not combined embodied carbon reduction with seismic design for CLT.

The innovations proposed should not compromise the strength or durability of structural and nonstructural components [19–21]. Building codes for seismic zones consider objectives to protect human life, although they inherently accept damage to both the structural and nonstructural systems [22], which can save lives, but at the same time can also mean high cost of repair or demolition [23], with repercussions for the life cycle of the building [10,24] and embodied carbon emissions [25].

However, research efforts have not yet achieved effective positioning of cross-laminated timber (CLT) in building systems [26], this relatively novel building material not having been affected by a severe earthquake [9]. Hence, any associated economic or environmental losses are yet unknown associated with the seismic event aftershocks and even triggered events such as fires, and little development has taken place regarding rehabilitation or reuse of components [27].

In terms of sustainability and the impact on carbon emissions of different materials, comparative studies have been undertaken [28–30], however these analyses are not focused on carbon emissions reduction for buildings in seismic zones. Dodoo et al. [31] and Shin et al. [32] have explored the potential of multi-story buildings, with a focus on the use of CLT-based elements, while Buck et al. [33] conducted research related to recycling and end-of-life phases of CLT by optimizing and replacing the material as part of the resource efficiency.

Different Lateral force-resisting systems have varying impacts on the performance of a structure. These systems include vertical systems such as shear walls, cores, bracing, and moment-resisting frames, as well as horizontal systems such as diaphragms and horizontal bracing [6]. Medel-Vera & Contreras [34] evaluated resilience using base isolation and Liang et al. [35] developed a case study for a 12-story building in Portland, Oregon USA. The results of their cradle-to-grave study using Life Cycle Assessment (LCA) over a period of 60 years indicated that timber construction requires 36% more gypsum plasterboard, and that the repair period impacts the life cycle assessment of the building.

In the experimental demonstrative field, a series of prototypes built under laboratory conditions have allowed the dynamic properties to be explored and the development of numerical models, such as SOFIE—Italy and Japan [19,36,37], being a project that has allowed a greater understanding of the use of CLT panels in the platform system in seismic zones; New Zealand [38] that have incorporated the post-tensioning system and dissipation elements; Tallwood Canada [39] recognized as a project that has impacted the entire value chain and which has used a concrete core that contributes to lateral stabilization; NHERI—USA [20] initiative has worked with post-tensioning systems and considered the use of diaphragms with different configurations, evaluating the damage; PymeLAB—Chile [40], dissemination initiative that combines platform and balloon systems, integrating disassembly strategies and continuous monitoring. Figure 1 presents two cases in which CLT structures were used, one being mid-rise laboratory level and the other high-rise residential, highlighting the use of a hybrid system in the latter.

(**a**) (**b**)

Figure 1. Examples of multi-storey CLT buildings in a seismic zone. (**a**) PymeLAB Concepción—Chile, 5-storey CLT structure; (**b**) Brock Commons Vancouver—Canada, 18-storey hybrid structure [39].

Innovation involves a continuous process of change in which a concept emerges then pertinent tests are developed to validate it [41], finally achieving the insertion of the solution into the market. The measurement of innovation and its indicators is a complex process, and it depends on different perspectives [42]. In this regard, to establish the degree of development of innovation from a technological perspective, the technological readiness levels (TRLs) have been developed [43].

To date, a series of tests on connections, lateral resistance systems, life cycle analysis, and the construction of prototypes under laboratory conditions have allowed for the exploration of different configurations, performance evaluation, dynamic properties, and the development of numerical models. However, which of these options considers the impact of the earthquake on the carbon footprint. This leads to the following research question: hat innovations and/or construction practices in CLT are used to reduce embodied carbon emissions in mid and high-rise timber construction in seismic zones, considering the entire life cycle?, What is the level of maturity of these technologies explored at the time of publication?, particularly for its due to its current relevance and given that it is an aspect not explored in other reviews.

This research work aims specifically to review the main innovations and CLT design practices that contribute to the reduction of embodied carbon emissions in medium and high-rise timber construction in seismic zones, exploring scientific studies published over the period from 2010 to 2025. The innovations assessed are those associated with structural design including global strategies, joint design and rational use of materials together with others associated with the secondary or non-structural elements and their possible reuse, substitution or repair.

2. Methodology

A systematic process was conducted to identify seismic design-oriented innovations and practices that in some way contribute to lowering the carbon embodied emissions. In accordance with the statement of elements established for a PRISMA review [44,45] (can be see PRISMA checklist in Supplementary Material), the process of reviewing the scientific literature was carried out in this work as shown in Figure 2.

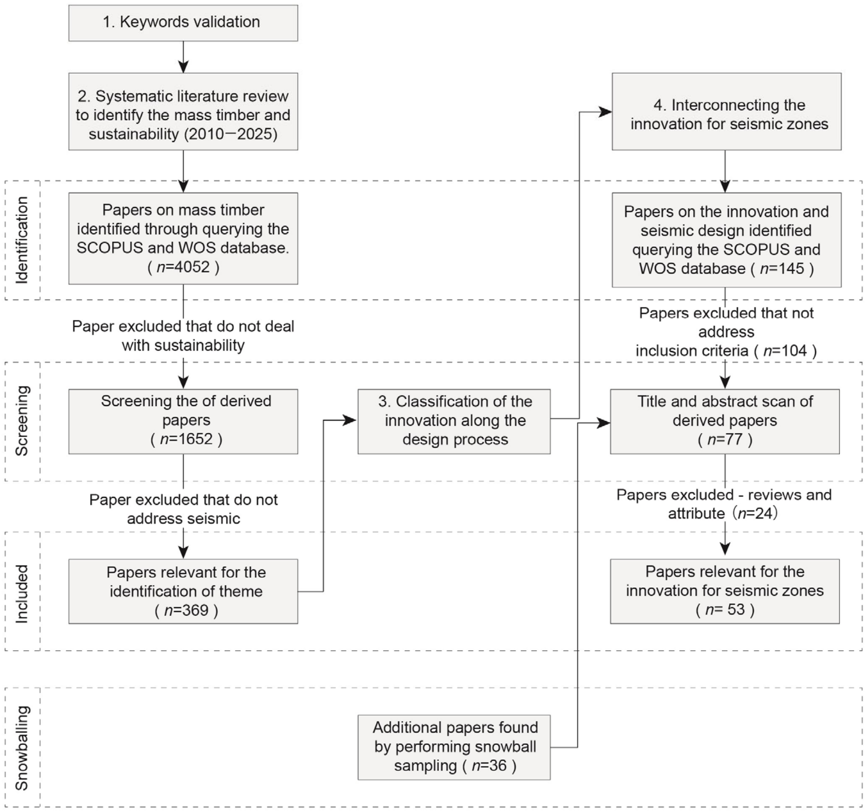

Figure 2. Flowchart of literature selection following PRISMA guidelines; (n = number of papers).

The keywords to be considered were collected through interviews with ten researchers. Their fields of specialization were architecture, wood engineering, structural engineering and the environment. Table 1 shows the key and secondary words collected, with an asterisk next to those considered for the present review. Based on these keywords, questions were developed using Boolean connectors (Table 1), and those used in the scientific databases Scopus and Web of Science. The search was limited to those references written in English and published between 1 January 2010 (given that the use of CLT has increased substantially since that year [46]) and 31 August 2025.

The search provided 145 possible articles for consideration. Of these, 104 documents were discarded because they did not meet the criteria sought, excluding articles which were not related to questions (Q1 to Q4), conference proceedings, editorial notes, thesis and duplicated papers, leaving 41 eligible documents within the scope of the research.

Following the previous analysis, a complementary related search was carried out selecting references cited in the 41 relevant papers, using the snowballing technique [47]. This analysis resulted in 36 additional papers of interest, including a relevant article from 2008, associated with Ceccotti [48]. The 77 pre-selected articles were analyzed, assessing the keywords, abstract and conclusion to confirm the relevance to the topic and to exclude reviews. We applied the inclusion criteria and 53 documents were finally chosen to develop the iterative coding process, in depth analysis and TRLs assignment. The documents finally considered were first analyzed using VOSviewer software version 1.6.20 (Centre for Science and Technology Studies, Leiden, The Netherlands) [49], visually revealing the interrelationship of the words in the texts, along with their frequency of occurrence, visually represented through the size of the word. In a second phase of analysis the contents of the selected articles were assessed, and the documents were subsequently organized into categories and subcategories, defined as "topics" using the open and axial coding method [50].

Table 1. Keywords query and criteria used for the search.

Keyword/ Query	Principal			
	Building	**Sustainability**	**Seismic**	**Innovation**
Secondary	Timber building Constructions * Mass Timber * Mid rise Design for adaptability Wood building Building Systems Green Building	Life cycle assessment Carbon reduction Circularity * Embodied carbon * Carbon footprint Zero Carbon Net Zero	Seismic performance Seismic protection Seismic design * Seismic force resisting systems Structural response	Green Innovation Strategies innovation Innovation potential Innovation process
Query	Q1: ("Mass Timber" AND ("Building" OR "Constructions")) Q2: ("Mass Timber" AND ("Building" OR "Constructions")); AND ("Sustainability" OR "Circularity" OR "Embodied carbon") Q3: ("Mass Timber" AND ("Building" OR "Constructions")); AND ("Sustainability" OR "Circularity" OR "Embodied carbon"); AND ("Seismic" OR "Seismic design") Q4: ("Mass Timber" AND ("Building" OR "Constructions")); AND ("Sustainability" OR "Circularity" OR "Embodied carbon"); AND ("Seismic" OR "Seismic design"); AND ("Innovation").			
Inclusion criteria	Article property metric (published in a journal and english language; not is review/perspective Paper). Article quality metric (research objective clearly given and is related current study; relationship to the research topics -directly or indirectly-; selection method clearly given; the data analysis process is clearly described; finding clearly given in the areas of study).			

* considered for the present review.

For the analysis and description of the innovations associated with the categories and subcategories, both seismic performance and reduction of embodied carbon were considered. Thus, in a zone of high seismic vulnerability, the use of life extension strategies such as those indicated in Figure 3 were considered, such as seismic resilient design, design for disassembly, adaptability, new functionalities for components, and R-strategies for a circular economy, to extend the life span and reduce embodied carbon.

Finally, a proposal was put forward for assessment using the TRLs metric in the different fields applicable to CLT buildings in seismic zones, according to the questions in Figure 4. The answer to these questions allowed the degree of maturity of technology described in the observed studies to be established.

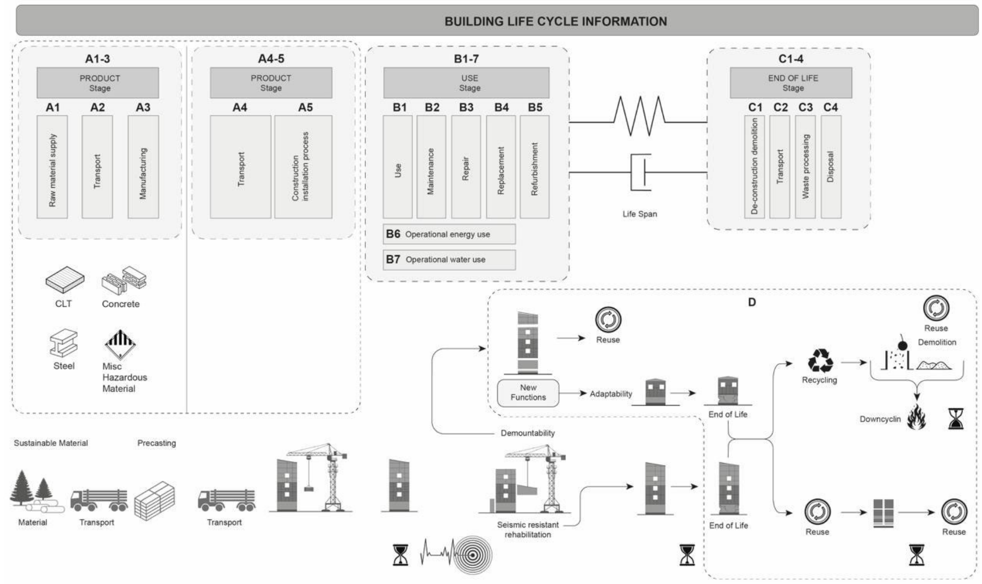

Figure 3. Illustration of building life cycle and earthquake recovery strategies (author's own diagram based on EN 15978:2011 [51]).

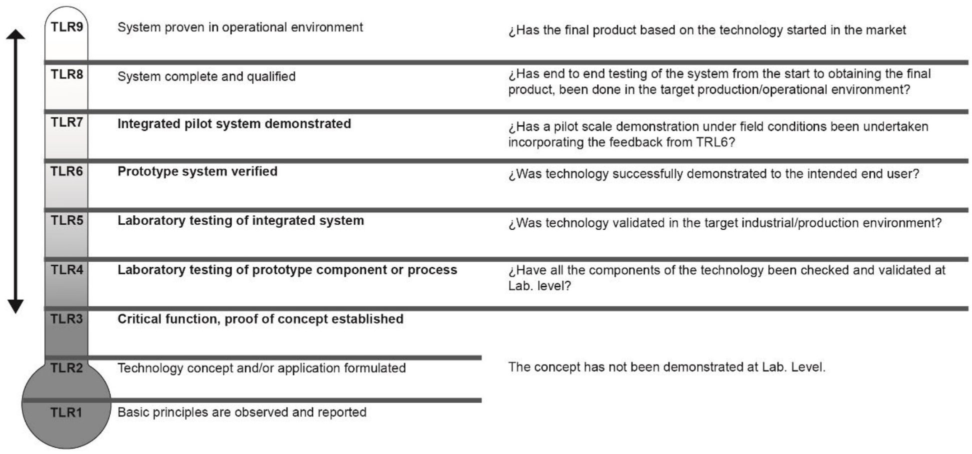

Figure 4. Defining of Technology Readiness Levels, modified from Fasterholdt et al. [52].

3. Results

3.1. General Analysis and Topic Identification

The initial R + D + i studies concerning elements and systems for timber buildings in seismic zones were those developed in Europe by Ceccotti. [48] and Sandhaas et al. [53]. Complementary research work with regard to connection systems, shear walls and structures was found in studies by Pei et al. [54], Popovski & Gavric [55], Hashemi et al. [56], Polastri et. al. [57], Connolly et al. [39], and Barbosa et al. [58].

The pioneering institutions in the field were those of the University of Venice and IVALSA. In recent years, important research has also been carried out by the University of Northern British Columbia—Canada, the University of Trento—Italy, the University of Auckland—New Zealand, Tongji University—Shanghai-China, and Oregon State University—USA.

The analysis of words performed using the VOS viewer applied to the title and abstract of the selected references revealed that most of the research focuses on the construction system, while less attention has been paid to innovation and carbon emissions as these aspects have only recently gained prominence.

Four clusters are evident using the above-mentioned tool on the complete texts of the references, mainly comprising topics related to connection, construction, CLT, and mechanical properties of the structure. The links between the most frequently used words are shown in Figure 5. Again, this graph highlights the scant presence of topics tacitly related to carbon emissions.

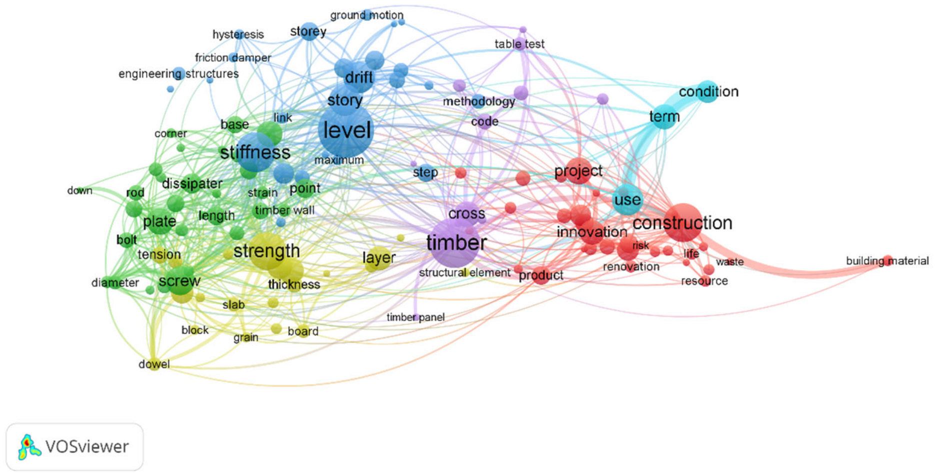

Figure 5. Network graph presenting co-ocurrence analysis of content for all the studies considered in the review.

A measure of strength between words indicates that innovation is related to construction and level. The term 'level' is highlighted, this term being related to damage, performance, and safety, all associated with the main reason for research to date, namely, structural performance.

The topics found using open and axial coding analysis [50] on all the selected references are presented in Table 2, associating the authors, sorted according to the year of publication and showing the categories and subcategories identified in the documents.

Table 2. Authors assigned to each category and subcategories, according to the main focus of the research.

Category	Subcategory	Author
Innovation	Adoption of initiatives	Zhong & Gou [59]; Poirier et al. [60].
	Connections	Latour & Rizzano [61]; Scotta et al. [62]; Hashemi et al. [56]; Polastri et al. [57]; Polastri et al. [63]; Trutalli et al. [64]; Fitzgerald et al. [65]; Hashemi et al. [66]; Moerman et al. [67]; Zhao et al. [68]; Assadi et al. [69]. Marchisella & Muciaccia [70]
	Monitoring	Longman et al. [71].
Sustainability	Material Selection	Vilguts et al. [72]; Buck et al. [73]; Sandhaas et al. [53]
	R strategy	Sun et al. [74]; Estrella et al. [75]; Riggio et al. [76].
	Renovation Solution	Tesfamariam et al. [77]; Marini et al. [78]; Stazi et al. [79]; Margani et al. [80]; Zanni et al. [81]; Badini et al. [82]; Smiroldo et al. [83].
Structural Performance	Construction System	Ceccotti, A. [48]; Ceccotti et al. [19]; Sandhaas et al. [53]; Yang et al. [84]
	Lateral System	Sarti et al. [38]; Bolvardi et al. [85]; Hashemi et al. [86]; Connolly et al. [39]; Ponzo et al. [87]; Sato et al. [36]; Sun et al. [88]; van de Lindt et al. [20]; Chen et al. [89]; Carrero et al. [90]; Khajehpour et al. [91]; Iezzi et al. [10]; Matteoni et al. [92]; Moerman et al. [93]; Araújo et al. [94]; Hashemi & Lal [95]; Lal et al. [96]; Wang et al. [97].; Tachibana et al. [98].
	Diaphragm	Loss & Davisson [99]; Ávila et al. [100]; Barbosa et al. [58].

The maturity level of the different technologies was also determined for the selected references. The results are shown in Table 3. It should be noted that the assignment of technology maturity status can be contrasted by using reference projects such as SOFIE and Brock Commons. These projects began with the concept (TRL2–TRL3) and concluded with a full-scale prototype and subsequent market use (TRL8–TRL9).

Table 3. TRL assignment according to categories and main focus of the reviewed research.

TRL	Innovation			Sustainability			Structural Performance		
	Adoption Initiatives	Connections	Monitoring	Materials Selection	R Strategy	Renovation	Construction System	Lateral System	Diaphragm
3					[76]				
4		[56,65,67,68]		[53]		[77–80,82]	[53]	[85,96]	[100]
5	[59]	[57,61–63,66,70]		[72,73]	[75]		[84]	[10,86–94,97]	[99]
6		[64]	[71]		[74]				[57]
7		[69]				[81,83]		[20,36,38,95,98]	
9	[60]						[16,48]	[39]	

It is evident that the technologies reaching the highest level of maturity (TRL9) are those from the early studies, the testing of platform-type CLT buildings having been conducted in relevant environments and subsequently these constructions have been observed in seismic zones in Europe. In turn, the Brock Commons project is a relatively recent one that incorporates innovations, is constructed in a seismic zone [39,60], and serves as a model for collaborative innovation, impacting the entire value chain with a TRL9 level. In contrast, at the lower levels, TRL3-TRL5, much of the research is carried out on samples of limited size or at structural size as a construction element in laboratory facilities., which is compared with the criteria indicated in Figure 4.

In summary, through the document analysis and according to open coding, it was possible to identify, as shown in Tables 2 and 3, three interrelated categories and subcategories with references that will be analyzed separately in the following sections.

3.2. Innovation Practices in CLT for Seismic Zones

3.2.1. Adoption of Initiatives

While many countries face challenges as regards sustainable, economic viability in the development of their infrastructure [60], technological advancements and political decisions are neither comparable nor homogeneous among countries. Adopting practices for the effective use of building systems which are both innovative and more environmentally efficient is critical given that the construction sector is highly regulated.

In this regard, initiatives and guidelines may provide support for innovative wood-based construction, as is the case of Canada, where high-rise timber construction has been promoted and demonstrated through initiatives put into practice by local public agencies, improving visibility and encouraging regulatory change [39]. This has been facilitated by collaborative innovation projects through innovation clusters [60], oriented towards environmental commitments on carbon and regulatory changes.

However, in other countries such as the USA, the adoption of CLT has been hindered by the lack of design codes for regions with high seismic activity [59]. Therefore, it is crucial to understand the local context and practices in order to promote solutions which are adapted to disaster hazards and, in the case of high seismic risk areas, to seek cost-competitive solutions for a low-carbon economy, such as the initiative driven by the FEMA code [101], which introduced four damage classes; the first of which requires a residual story drift of less than 0.2% when considering a structural realignment.

The building and structural codes utilized in the assessed researches about structural performance of CLT in seismic areas are the following ones: Eurocode 8 [19,53], GB50011 [88]; NCh433 [90,100]; NZS 1170.5 [69]; FEMA 273 [100]; FEMA P695 [20,85,91]; ASCE 7-16 [20,36,85,100]; and CSA-086 [39,91].

3.2.2. Innovative Connections

Although review studies which focus on the connections in CLT buildings have been conducted, providing valuable insights and improved understanding [13,102], this issue has been reviewed in the present work from the perspective of innovations aimed at reducing the carbon footprint in seismic areas, this perspective not having been adopted previously by other authors.

In relation to seismic performance, efforts have been channeled into researching and improving the resilience of CLT in terms of connections, thus meeting the objectives in stages B and D of the life cycle (Figure 3), as shown in the absorption and dissipation of energy reported by Assadi et al. [69], who included the results for a wall-to-wall and wall-to-beam joint which uses a mechanism that eliminates a significant number of connections in the transfer of lateral loads, thus increasing the resilience of the structure.

Scotta et al. [62] and Trutalli et al. [64] compared traditional joints and innovative replaceable elements such an X-bracket, in which the dissipative component is located in the hardware providing ductility and energy dissipation capacity, while the anchoring to the CLT panel ensures elastic deformation. After suffering certain levels of seismic intensity, the damaged connector can easily be replaced (stage B4 on reuse—Figure 3).

Zhao et al. [68] proposed a connection method for joints between H-type metal profiles and wooden elements such as laminated beams, LVL, or CLT. The method involves activating a particular failure mode in the pin, creating a double plastic hinge. The connection has the drawback of adding an additional step to the construction process, as well as another material of a different nature, which becomes a problem during disassembly or reuse, stages B and D of the life cycle.

Moerman et al. [67] designed and tested a connection applied to the lateral load resistance system formed by CLT panels and steel beams. The proposal is based on the tensioning of bars. There will be a loss of tension over time in this system due to the nature of wood; thus the design must allow for maintenance (B2—Figure 3).

Latour & Rizzano [61] proposed a new type of hold-down called the XL-stud, which shifts the dissipative zone of the hold-down from the stem to the flange plate. In a similar approach whereby a failure area or mechanical fuse is created, in the case of the hold-down these are free fasteners. Marchisella & Muciaccia [70] presented and assessed a hold-down design in which the failure obtained corresponds to the buckling of the flange at a specific point. In general, these innovations meet the objectives of stages B and D of the life cycle (Figure 3), as the timber-to-steel interaction is elastic and thus the CLT panel remains undamaged.

Polastri et al. [63] developed a connection system for CLT called the X-RAD, with a single connector type positioned at the corners of the CLT panels. The system is fixed, with self-tapping fully threaded screws as an alternative to both the hold downs and the shear angular brackets [63]. This connection system presents a good level of ductility and high energy dissipation capacity. Furthermore, the system is versatile and simple, regardless of the 3D geometrical design configurations, and it fulfills the objectives in stages B and D of the life cycle (Figure 3).

Finally, Hashemi et al. [56], Hashemi et al. [66] and Fitzgerald et al. [65] developed a connection system with passive sliding friction dampers, reducing damage to joints by dissipating energy through friction, which can notably improve certain aspects of the seismic performance in coupled timber walls. This negatively impacts stage A, but benefits stage B and D of the life cycle.

In summary, the carbon footprint in seismic areas can be reduced by facilitating the replacement of connections once damaged, thus extending the life of the building while keeping the advantage of low carbon footprint associated with the CLT construction. Furthermore, expected damage to the building is reduced by improving the performance of connections. In this regard damage to the CLT elements is mitigated by changing the failure mode of the connections or increasing their resilience. Other strategies are oriented towards reducing the damage expected in the connections using, for example, friction-based energy dissipation designs.

3.2.3. Monitoring

Longman et al. [71] defined an implementation methodology for a digital twin, which represents spatial details, captures physical properties of the material, and allows continuous monitoring of a post-tensioned system, the latter providing a damage detection strategy. This innovation was installed in the 'Peavy Hall' building at Oregon State University. It consists of sensors that enable both the structural health and moisture content of the components to be monitored. Structural health monitoring provides a damage detection strategy involving the use of sensors, a data acquisition system, and algorithms for the processing and analysis. The system was tested in a case study in two stages, the first during the construction and the second once the building was operative.

During the first stage, tension loss in the system was identified, necessitating retensioning, which is crucial for buildings in seismic zones to ensure the behavior anticipated in the design (stage A5—Figure 3). In the second stage, the system becomes a management support facilitating maintenance interventions and early warnings.

3.3. Progress on CLT Sustainability That Can Be Applied to Seismic Zones

The following sections examine recent advances that enhance the sustainability of CLT construction in seismic areas, focusing on three complementary dimensions: material selection aimed at reducing embodied carbon and improving structural efficiency, the adoption of "R strategies" (repair, replacement, refurbishment, reuse, and recycling) to extend the life cycle of buildings, and renovation solutions that integrate CLT into existing structures to improve seismic resilience while minimizing environmental impact.

3.3.1. Materials Selection

In terms of improving mechanical performance, Buck et al. [73] introduce a novel glued CLT panel configuration with layers oriented at 45°, which, for certain structural performances, would reduce the amount of timber used, contributing to a more efficient stage A (Figure 3). Sandhaas et al. [53] used dowel-laminated timber (DLT) panels and applied lifecycle module D strategies, associated with the reuse and recycling of similar materials. Vilguts et al. [72] presented a development for creating shear connections between wall-wall, slab-slab, and slab-wall, using hardwood dowels made of red oak and birch species with two diameters, the aim being to replace metal connectors to achieve a reduction in embedded carbon.

The importance of the above mentioned reduction in the use of metal connectors can be understood by examining the data in Cecotti et al. [19]. These authors reported a consumption of 4.5 tons of metal fittings and connectors for a 7-story CLT building tested on a seismic table. This result suggests a consumption of 2.08 kg per linear meter of structural segmented wall or 8.33 kg per square meter constructed.

3.3.2. R Strategy (Repair, Replacement, Refurbish, Reuse and Recycling)

Due to the cyclical nature and intensity of earthquakes, especially in areas where they are of high intensity, significant, permanent damage to wooden panels may be acceptable [10], as long as it does not compromise the structural safety. However, if the design does not consider strategies for adaptability and if either total or selective dismantling of the components is required, especially of structural joints or nonstructural elements, a higher carbon footprint during both the service and the end-of-life stages (stages B, C and D respectively—Figure 3) may result. Furthermore, there will be works and costs associated with the demolition and reconstruction of structural and nonstructural components, which can severely impact carbon emissions [101].

Fragility analysis, taking into consideration the inter-story drift residual value, stands out as a method for post-earthquake evaluation of a structure, both for reasons of safety evaluation and for the feasibility of repair and reconstruction [74].

Product design strategy can consider deconstruction and reuse over several lifespans [75]. By employing reversible connections, the aim is to maximize the open-ended reuse potential of building components.

In research undertaken by Riggio et al. [76] to develop a typology of modular systems, the authors describe the criteria used to design a proposed solution for self-standing, load bearing, reusable and flexible load bearing wood furniture modules which are integrated into the structure. The design considers the spatial requirements of the other systems to ensure accessibility, independence between shearing layers and enhance reversibility. In the case of a seismic event, these authors recommend a 7 mm tolerance to allow sliding between load-bearing wood furniture modules, and they highlight the difference in material quantity usage when the system is employed in an area where the demands are particularly high.

In summary, for areas with high seismic risk, it is necessary to consider the use of suitable solutions for severe movements and displacements between the structure and enclosures. Hence, conceptual design plays a role in combining damage limitation, resilience, costs associated with the maintenance stages (B2-5 in Figure 3), and optimization of the life cycle of CLT buildings [6]. During the service stage, there may be requirements for repair, replacement or refurbishment while beyond the life cycle the reuse, repurposing and recycling of components all allow for increased sustainability of a solution. Therefore, building innovations should be conceived such that joints may be disassembled and components detached, while other solutions such as the use of gaps or flexible gaskets can be employed to reduce damage to nonstructural elements.

3.3.3. Renovation Solutions

Tesfamarian et al. [77], Marini et al. [78], Zanni et al. [81] and Badini et al. [82] presented solutions for repairing existing reinforced concrete (RC) structures using CLT as the renovation material. The use of CLT provides a renovation solution that enhances seismic resilience, extends the service life, and minimizes intervention time in damaged structures following an earthquake.

Margani et al. [80] and Smiroldo et al. [83] present a system that incorporates CLT panels into RC structures with the aim of reducing weight in the context of improved lateral stiffness of the structure to reduce inter-story drift under seismic demands. This system is supported by a connector that acts as an energy dissipator against seismic demands. Similarly, Stazi F. et al. [79] developed a concept for the rehabilitation of structures using CLT panels inserted within a frame. All these solutions aim to rehabilitate the built environment in seismic zones, contributing to a reduction of the carbon footprint, extending the service life, and avoiding the demolition of existing structures.

Figure 6 shows that topics related to the sustainability strategies in seismic zones have attracted the attention of researchers.

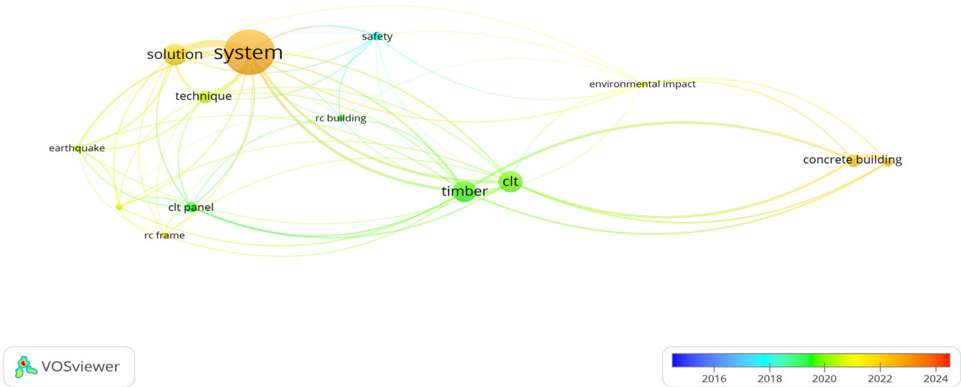

Figure 6. Network graph presenting co-ocurrence analysis of content for Progress on CLT sustainability considered in the review.

3.4. Research on CLT Structural Performance Improvement for Seismic Zones

3.4.1. Construction System

Sandhaas et al. [53] investigated different innovative construction elements to be used in seismic zones as an alternative to traditional CLT panels. They considered elements built using dowels (DLT) and glued elements with spaces (CLTi). The former is of particular interest where materials of the same nature require disassembly, and the latter implies savings in terms of materials.

At the level of the elements themselves, the DLT showed ductile failure as the connectors (brackets) fixing the plates developed plastic hinges, with significant displacements (between 61 and 146 mm). This is not compatible with the behavior of non-structural elements. In contrast, the CLTi walls with brackets reached the highest load capacities considering the drift limit (2%—5 mm).

Yang et al. [84] used balloon-type cross-laminated timber for a 12 story building in Vancouver and Montreal. They compared the adjustable collapse margin ratio with limits recommended by FEMA P695 [103] and found that the adjusted collapse margin ratio was sufficient.

3.4.2. Lateral Stabilization System

As regards post-tensioned systems, Sarti et al. [38] and Iezzi et al. [10] addressed this issue in a comprehensive manner, relating the connections and the need to concentrate dissipative behavior in plug-and-play-type elements to facilitate maintenance, disassembly, and reuse. As for resilience, damage control is applied to both structural and nonstructural elements given that in both cases it is necessary to bear in mind the consequences of demolition, recycling, and aspects associated with the results of an LCA analysis, which was in line with carbon reduction.

Tachibana et al. [98] used post-tensioning and hysteretic energy dissipation devices as part of a collaborative research effort (NHERI TallWood project). No notable structural damage or residual drift was found and a very resilient swing wall with excellent recentering capabilities was obtained, with less than 2% inter-story drift (7 mm).

Ponzo et al. [87] describe a low-damage seismic design procedure for structures with a post-tensioned lateral resistance system, coupled with a dissipative reinforcement system aimed at preventing damage to structural and nonstructural components. This highly valued innovative practice defines the desired performance level such that damage and the need for replacement is avoided (stage B-Figure 3), although it must be accompanied by the respective economic evaluation and carbon reduction goal.

Matteoni et al. [92] developed a framework using fragility curves for the analysis of both connections and the lateral system formed by the Pres Lam system, comparing different approaches through a nonlinear pushover analysis, as described by other authors [36,81,85,91] and complementing the information with dynamic time history analysis [71,83,85,87,90,92].

In a construction with the platform system using segmented walls, Sato et al. [36] conducted a study involving the design and testing of a five-story building with CLT elements featuring different wall configurations. From a seismic perspective, the construction practice using narrow segmented panels can be recommended, taking into account the limits established by the Japanese regulations for structures, which limit the inter-story drift to 0.5% for minor damage level and to 2.2% for safety level [36]. Although the model was successfully tested, the drift levels achieved would cause damage to nonstructural components, particularly if there are no design strategies that consider displacement and/or tolerances in the construction solution, thus affecting not only rehabilitation costs but also the carbon footprint in stages B and D.

Considering hybrid CLT-steel solutions with the aim of reducing the carbon footprint, Khajehpour et al. [91] compared the construction system in seismic zones with the construction system involving the use of steel-based frames. The hybrid solution was projected as an economical and sustainable option for medium and high-rise buildings. Structural hybridization provides the possibility of increasing stiffness while maintaining load-bearing capacity, with the main advantage being the weight reduction of elements by eliminating metal components, thus leading to a decrease in the seismic forces.

Along the same lines, Connolly et al. [39] conducted a comparative study on an 18-story building constructed on a concrete podium using two strategies: concrete cores or cores made of CLT or Laminated Veneer Lumber. The numerical models and the type of wooden structural element used revealed that it is feasible to employ central wooden cores in symmetrical shapes, providing an environmental advantage to the solution. The life cycle analysis was developed and compared for the different solutions in the Cradle to Gate stages for each impact category, establishing a baseline with RC (100%). For the Global Warming Potential impact category, the CLT solution showed a 30% lower impact, underlining the hybrid construction practice as a viable solution in seismic zones.

Regarding the use of seismic protection systems, in research conducted by Bolvardi et al. [85]; Hashemi et al. [86] and Lal et al. [96] they employed base isolation and used the Displacement-based Direct Design procedure. Energy dissipation occurs in the seismic isolation device and the CLT structure behaves elastically, favoring resilience. The application of the inter-story isolation concept in the platform system for CLT buildings is an innovative practice for seismic zones, demonstrating the benefits of this type of isolation as regards damage reduction, although it entails a higher initial investment cost, which must be evaluated bearing in mind the principles of FEMA [101] and the corresponding economic analyses.

Wang et al. [97] compared two types of construction systems, with two types of supplemental energy dissipators and found that the O-shaped Flexural Plate dissipator installed in the balloon system was able to dissipate more energy.

As previously mentioned, several attempts have been made by researchers to develop a lateral stabilization system, but it is evident that it is not possible to address the lateral system alone without considering innovations aimed at reducing the lateral seismic drift, particularly where this is associated with the performance of connections and therefore the level of damage expected as a result of a severe earthquake occurrence.

The main innovations assessed in this review include contributions to post-tensioned systems [10,20,38,87–89], segmented walls [36], hybrid solutions [90,91], and seismic protection systems [85,86,93,96,97]. The main objective in some of these systems is that of ductile behavior for energy dissipation, with reduced inter-drift to avoid damage.

Figure 7 shows that topics related to the lateral stabilization system in seismic zones have attracted the attention of researchers.

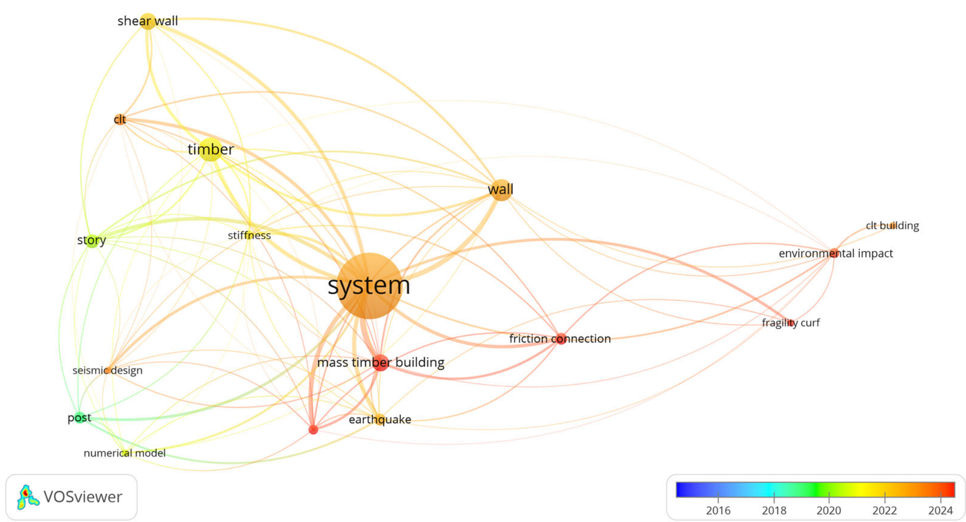

Figure 7. Network graph presenting co-ocurrence analysis of content for Lateral Stabilization System considered in the review.

3.4.3. Diaphragm Performance

In this regard, Assadi et al. [69] developed an innovative connection, highlighting the incompatibility that exists between the rocking motion generated in the wall elements in relation to the diaphragm, which can cause severe damage or crushing of panel edges. This is undesirable in terms of resilience, as it implies greater damage and complicates potential replacement in stage B of the life cycle, involving disassembly stages, especially in the case of the platform system. In this case, design strategies for adaptability and disassembly should be considered to take into consideration the carbon footprint.

Ávila et al. [100] evaluated the effect of diaphragm classification applied to hybrid buildings. The classification was developed according to the flexibility index and showed that as the flexibility of the diaphragm increases, the base shear and inter-story drift do not increase significantly, which is of particular interest in the design phase.

In line with hybrid construction, Barbosa et al. [58] conducted experimental work on a seismic table for a two-story structure based on laminated wood columns and beams, using CLT panels for the walls and slabs. Two types of diaphragms were examined for the structure: CLT panels and CLT panels coupled with a concrete slab. An innovative connection between the walls and diaphragms was made using a steel key which was connected by bolts to the wall with screws inserted at 45° to the diaphragm. Subsequent tests revealed no significant failures in the diaphragm. The diaphragm with concrete was found to be more favorable as cracks occurred in the connection areas of the inclined screws. Although the use of this type of combination of materials complicates the reuse or recycling of the elements it results in less damage to the diaphragms. Hence, the alternatives should be evaluated in terms of disassembly for repair and the potential for recycling (Figure 3).

Similarly, Loss and Davison [99] developed an innovative steel-timber composite floor for use in multi-storey residential buildings. Their research demonstrates the potential of these steel-timber composite systems in terms of bearing capacity, stiffness and method of construction. These systems simplify the on-site execution, reduce construction time and costs as well as increasing the sustainability of the final construction system thanks to the use of recyclable, natural materials and to the capacity for deconstruction and reuse of the structural components.

4. Conclusions

This paper presents a comprehensive systematic review of innovations and applied research on CLT buildings located in areas of high seismic risk, with particular attention to reducing embodied carbon. The analysis, covering studies published between 2010 and 2025 and supported by TRL assessment, identified contributions that can be organized into three interrelated dimensions: innovation practices, sustainability progress, and structural performance improvements.

Although considerable advances have been made in improving the seismic performance of CLT construction, the explicit integration of environmental considerations into structural innovation remains limited. Future research should therefore multicriterial aim to strengthen the connection between seismic resilience, embodied carbon reduction, and life-cycle design strategies to fully harness the potential of CLT as a sustainable construction solution in seismic regions. Particular emphasis should be placed on practices related to life-cycle stages B and D, where the extension of building service life and the reduction of post-event impacts can significantly improve overall performance in areas of high seismic vulnerability. It is worth noting that this review focused exclusively on scientific literature; therefore, information contained in patents or commercial applications was not considered. Additionally, aspects such as soil–structure interaction, fire compartmentation loss, and aftershock risk were beyond the scope of this analysis.

Innovation practices

Innovation practices are being increasingly promoted through initiatives led by public agencies and innovation clusters, improving the visibility and acceptance of timber-based solutions in the construction sector. Regulatory reforms, such as those accompanying the emergence of high-rise timber buildings in Canada, illustrate how supportive policy frameworks can accelerate the adoption of such technologies. Nonetheless, further innovation is needed to enhance the performance of CLT structures in terms of embodied carbon reduction and post-seismic reparability, particularly regarding potential damage to structural and non-structural elements. Notably, the development of replaceable connection systems and controlled failure mechanisms represents a crucial step toward resilient, low-impact construction. The review highlights several key advances in this domain, together with the growing potential of sensor-based monitoring systems that allow real-time tracking of structural responses, post-tensioned components, and moisture conditions. These innovations enable early detection of anomalies and proactive maintenance, thereby improving building reliability both during and after seismic events.

Progress on sustainability

Progress toward sustainability has been equally significant, emphasizing material-efficient strategies such as the use of dowel-laminated timber, timber-based connectors, and optimized lamination angles to enhance mechanical and environmental performance. Beyond material optimization, life-cycle considerations have gained prominence—especially regarding dismantling, reuse, and recycling of components. Design strategies that facilitate accessibility, reparability, and modularity are fundamental to maximizing environmental benefits in seismic contexts, as they reduce embodied carbon while preserving structural integrity. Likewise, the application of CLT in renovation and retrofitting projects illustrates the potential of timber systems to improve environmental performance through recovery, repair, and reuse approaches aligned with circular economy principles.

Structural performance improvement

Enhancements in structural performance remain at the core of CLT innovation in seismic areas. Key advances relate to the reduction of lateral drift, the enhancement of global resilience, and the minimization of damage-related carbon impacts. These objectives require considering not only the performance of structural components but also that of non-structural elements, aiming for drift limits typically below 0.5%. In highly seismic regions, such parameters should be treated as design requirements to ensure maximum component longevity and to enable strategies such as base isolation, decoupling, and tolerance design. These approaches contribute both to improved structural behavior and to lower embodied carbon impacts, with additional benefits related to cost efficiency and fire safety.

The review also documents the evolution of lateral stabilization systems, including post-tensioned, dissipative, and isolation-based solutions, all seeking to enhance structural resilience while reducing the carbon footprint associated with damage and repair. The diaphragm effect of CLT panels remains a promising area of research, with hybrid configurations—combining timber with steel or concrete—showing particular potential for achieving a balanced trade-off between strength, stiffness, and sustainability. Modular and prefabricated approaches further reinforce these benefits by improving constructability and reducing waste.

Despite these advances, explicit assessments of environmental impacts in seismic performance studies remain scarce. The TRL-based evaluation conducted in this research underscores these gaps and points to the need for integrated frameworks where sustainability metrics are systematically incorporated into seismic design and assessment methodologies.

Overall, this review highlights the growing convergence between innovation, sustainability, and resilience in CLT construction. Future progress will depend on interdisciplinary collaboration among engineers, material scientists, architects, and policymakers to accelerate the transition from experimental prototypes to market-ready, low-carbon, and seismically resilient building systems.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/buildings15224141/s1, Table S1: PRISMA checklist. Ref. [104] is cited in the Supplementary Materials.

Author Contributions: Conceptualization, V.R., E.L., S.Á. and C.A.-P.; Methodology, V.R. and C.A.-P.; Investigation, V.R.; Writing—original draft, V.R.; Writing—review & editing, E.L. and C.A.-P.; Visualization, V.R.; Funding acquisition. V.R. and C.A.-P., Supervision. E.L., S.Á. and C.A.-P.; Project administration, C.A.-P., Resources, C.A.-P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Universidad Politécnica de Madrid and Universidad del Bío-Bío, the latter in through project grant ANID ID24I10158. In addition, the authors thank ANID BASAL FB210015 and scholarship Fundación Carolina-Spain for their ongoing scientific collaboration with our academic departments. The results and opinions in this paper are solely of the authors and do not represent the sponsor opinion.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Pelletier, C.; Rogaume, Y.; Dieckhoff, L.; Bardeau, G.; Pons, M.-N.; Dufour, A. Effect of combustion technology and biogenic CO2 impact factor on global warming potential of wood-to-heat chains. *Appl. Energy* **2019**, *235*, 1381–1388. [CrossRef]
2. United Nations Environment Programme. Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. 2021. Nairobi. Available online: www.globalabc.org (accessed on 24 January 2025).
3. Osuizugbo, I.C.; Oyeyipo, O.; Lahanmi, A.; Morakinyo, A.; Olaniyi, O. Barriers to the Adoption of Sustainable Construction. *Eur. J. Sustain. Dev.* **2020**, *9*, 150. [CrossRef]
4. Höhne, N.; den Elzen, M.; Rogelj, J.; Metz, B.; Fransen, T.; Kuramochi, T.; Olhoff, A.; Alcamo, J.; Winkler, H.; Fu, S.; et al. Emissions: World has four times the work or one-third of the time. *Nature* **2020**, *579*, 25–28. [CrossRef] [PubMed]
5. Anastasiadis, A.; Moşoarca, M. Earthquake Resilient near Zero Energy Buildings: Attributes and Perspectives. *Sustainability* **2024**, *16*, 2317. [CrossRef]
6. Hasani, N.; Riggio, M. Achieving circular economy through adaptable design: A comparative analysis of literature and practice using mass timber as a case scenario. *J. Build. Eng.* **2025**, *100*, 111802. [CrossRef]
7. Fang, D.; Brown, N.; De Wolf, C.; Mueller, C. Reducing embodied carbon in structural systems: A review of early-stage design strategies. *J. Build. Eng.* **2023**, *76*, 107054. [CrossRef]
8. Abdolmaleki, H.; Ahmadi, Z.; Hashemi, E.; Talebi, S. A review of the circular economy approach to the construction and demolition wood waste: A 4 R principle perspective. *Clean. Waste Syst.* **2025**, *11*, 100248. [CrossRef]
9. Ugalde, D.; Almazán, J.L.; María, H.S.; Guindos, P. Seismic protection technologies for timber structures: A review. *Eur. J. Wood Wood Prod.* **2019**, *77*, 173–194. [CrossRef]
10. Iezzi, S.; Savini, F.; Trizio, I.; Fabbrocino, G.; Sandoli, A. On the Role of Seismic Damage Tolerance on Costs and Life Cycle of CLT Buildings. *Appl. Sci.* **2023**, *13*, 9113. [CrossRef]
11. Junda, E.; Málaga-Chuquitaype, C.; Chawgien, K. Interpretable machine learning models for the estimation of seismic drifts in CLT buildings. *J. Build. Eng.* **2023**, *70*, 106365. [CrossRef]
12. Tannert, T.; Loss, C. Contemporary and Novel Hold-Down Solutions for Mass Timber Shear Walls. *Buildings* **2022**, *12*, 202. [CrossRef]
13. Li, Z.; Tsavdaridis, K.D. Design for Seismic Resilient Cross Laminated Timber (CLT) Structures: A Review of Research, Novel Connections, Challenges and Opportunities. *Buildings* **2023**, *13*, 505. [CrossRef]
14. Mohammadi, J.; Ling, L. Can Wood Become an Alternative Material for Tall Building Construction. *Pract. Period. Struct. Des. Constr.* **2017**, *22*, 4017014. [CrossRef]
15. Sandhaas, C.; Sarnaghi, A.K.; van de Kuilen, J.-W.G. Numerical modelling of timber and timber joints: Computational aspects. *Wood Sci. Technol.* **2019**, *54*, 31–61. [CrossRef]
16. Luo, J.; He, M.; Li, Z.; Ou, J.; He, G. Seismic performance evaluation of glulam structures with either braced frames or knee-braced frames as the main lateral load resisting system. *Soil Dyn. Earthq. Eng.* **2020**, *154*, 107134. [CrossRef]
17. Moussavi Nadoushani, Z.S.; Akbarnezhad, A. Effects of structural system on the life cycle carbon footprint of buildings. *Energy Build.* **2020**, *102*, 337–346. [CrossRef]
18. Sandoli, A.; D'Ambra, C.; Ceraldi, C.; Calderoni, B.; Prota, A. Sustainable Cross-Laminated Timber Structures in a Seismic Area: Overview and Future Trends. *Appl. Sci.* **2021**, *11*, 2078. [CrossRef]
19. Ceccotti, A.; Sandhaas, C.; Okabe, M.; Yasumura, M.; Minowa, C.; Kawai, N. SOFIE project–3D shaking table test on a seven-storey full-scale cross-laminated timber building. *Earthq. Eng. Struct. Dyn.* **2013**, *42*, 2003–2021. [CrossRef]
20. van de Lindt, J.W.; Furley, J.; Amini, M.O.; Pei, S.; Tamagnone, G.; Barbosa, A.R.; Rammer, D.; Line, P.; Fragiacomo, M.; Popovski, M. Experimental seismic behavior of a two-story CLT platform building. *Eng. Struct.* **2019**, *183*, 408–422. [CrossRef]
21. Bianchi, S.; Ciurlanti, J.; Perrone, D.; Filiatrault, A.; Costa, A.C.; Candeias, P.X.; Correia, A.A.; Pampanin, S. Shake-table tests of innovative drift sensitive nonstructural elements in a low-damage structural system. *Earthq. Eng. Struct. Dyn.* **2021**, *50*, 2398–2420. [CrossRef]
22. Miranda, E.; Mosqueda, G.; Retamales, R.; Pekcan, G. Performance of Nonstructural Components during the 27 February 2010 Chile Earthquake. *Earthq. Spectra* **2012**, *28*, 453–471. [CrossRef]
23. Rashid, M.; Dhakal, R.; Sullivan, T. Seismic design of acceleration-sensitive non-structural elements in New Zealand: State-of-practice and recommended changes. *Bull. N. Z. Soc. Earthq. Eng.* **2021**, *54*, 243–262. [CrossRef]
24. Watari, T.; Yamashita, N.; Serrenho, A.C. Net-Zero Embodied Carbon in Buildings with Today's Available Technologies. *Environ. Sci. Technol.* **2024**, *58*, 1793–1801. [CrossRef] [PubMed]
25. Huang, M.; Simonen, K. Comparative Environmental Analysis of Seismic Damage in Buildings. *J. Struct. Eng.* **2020**, *146*, 05019002. [CrossRef]

26. Benedetti, F.; Rosales, V.; Opazo-Vega, A.; Norambuena-Contreras, J.; Jara-Cisterna, A. Experimental and numerical evaluation of hold-down connections on radiata pine Cross-Laminated-Timber shear walls: A case study in Chile. *Eur. J. Wood Wood Prod.* **2019**, *77*, 79–92. [CrossRef]
27. Vamza, I.; Diaz, F.; Resnais, P.; Radzin, A.; Blumberga, D. Life cycle assessment of reprocessed cross laminated timber in Latvia. *Environ. Clim. Technol.* **2021**, *25*, 58–70. [CrossRef]
28. Jayalath, A.; Navaratnam, S.; Ngo, T.; Mendis, P.; Hewson, N.; Aye, L. Life cycle performance of Cross Laminated Timber mid-rise residential buildings in Australia. *Energy Build.* **2020**, *223*, 110091. [CrossRef]
29. Allan, K.; Phillips, A.R. Comparative Cradle-to-Grave Life Cycle Assessment of Low and Mid-Rise Mass Timber Buildings with Equivalent Structural Steel Alternatives. *Sustainability* **2021**, *13*, 3401. [CrossRef]
30. Hawkins, W.; Cooper, S.; Allen, S.; Roynon, J.; Ibell, T. Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure. *Structures* **2021**, *33*, 90–98. [CrossRef]
31. Dodoo, A.; Truong, N.L.; Nguyen, T.; Dorn, M.; Olsson, A.; Bader, T.K. Exploring the synergy between structural engineering design solutions and life cycle carbon footprint of cross-laminated timber in multi-storey buildings. *Wood Mater. Sci. Eng.* **2021**, *17*, 30–42. [CrossRef]
32. Shin, B.; Wi, S.; Kim, S. Assessing the environmental impact of using CLT-hybrid walls as a sustainable alternative in high-rise residential buildings. *Energy Build.* **2023**, *294*, 113228. [CrossRef]
33. Buck, D.; Wang, X.A.; Hagman, O.; Gustafsson, A. Comparison of Different Assembling Techniques Regarding Cost, Durability, and Ecology—A Survey of Multi-layer Wooden Panel Assembly Load-Bearing Construction Elements. *BioResources* **2015**, *10*, 8378–8396. [CrossRef]
34. Medel-Vera, C.; Contreras, M.C. Resilience-based predictive models for the seismic behaviour of mid-rise, base-isolated CLT buildings for social housing applications in Chile. *J. Build. Eng.* **2021**, *44*, 103397. [CrossRef]
35. Liang, S.; Gu, H.; Bergman, R.D. Environmental Life-Cycle Assessment and Life-Cycle Cost Analysis of a High-Rise Mass Timber Building: A Case Study in Pacific Northwestern United States. *Sustainability* **2021**, *13*, 7831. [CrossRef]
36. Sato, M.; Isoda, H.; Araki, Y.; Nakagawa, T.; Kawai, N.; Miyake, T. A seismic behavior and numerical model of narrow paneled cross-laminated timber building. *Eng. Struct.* **2019**, *179*, 9–22. [CrossRef]
37. Nakano, K.; Karube, M.; Hattori, N. Environmental Impacts of Building Construction Using Cross-laminated Timber Panel Construction Method: A Case of the Research Building in Kyushu, Japan. *Sustainability* **2020**, *12*, 2220. [CrossRef]
38. Sarti, F.; Palermo, A.; Pampanin, S. Quasi static cyclic testing of two-thirds scale un-bonded posttensioned rocking dissipative timber walls. *J. Struct. Eng.* **2016**, *142*, E40115005. [CrossRef]
39. Connolly, T.; Loss, C.; Iqbal, A.; Tannert, T. Feasibility Study of Mass-Timber Cores for the UBC Tall Wood Building. *Buildings* **2018**, *8*, 98. [CrossRef]
40. Rosales, V.; Benedetti, F.; Suazo, M.; Vargas, M.; Rojas, I.; Jara, A.; Rebolledo, A. Associativity between SMEs towards mid-rise building timber construction: PymeLab Project. In Proceedings of the World Conference on Timber Engineering, Santiago, Chile, 9–12 August 2021.
41. da Silva, F.M.; Oliveira, E.A.d.A.Q.; de Moraes, M.B. Innovation development process in small and medium technology-based companies. *RAI Rev. Adm. Inovação* **2016**, *13*, 176–189. [CrossRef]
42. Dziallas, M.; Blind, K. Innovation indicators throughout the innovation process: An extensive literature analysis. *Technovation* **2019**, *80–81*, 3–29. [CrossRef]
43. Bhattacharya, S.; Kumar, V.; Nishad, S.N. Technology Readiness Level: An Assessment of the Usefulness of this Scale for Translational Research. *Productivity* **2022**, *62*, 112–124. [CrossRef]
44. Wolfswinkel, J.F.; Furtmueller, E.; Wilderom, C.P.M. Using grounded theory as a method for rigorously reviewing literature. *Eur. J. Inf. Syst.* **2013**, *22*, 45–55. [CrossRef]
45. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. Declaración PRISMA 2020: Una guía actualizada para la publicación de revisiones sistemáticas. *Rev. Española Cardiol.* **2021**, *74*, 790–799. [CrossRef]
46. Ren, H.; Bahrami, A.; Cehlin, M.; Wallhagen, M. Proposing New Adhesive-Free Timber Edge Connections for Cross-Laminated Timber Panels: A Step Toward Sustainable Construction. *Case Stud. Constr. Mater.* **2024**, *20*, e02975. [CrossRef]
47. Jalali, S.; Wohlin, C. Systematic literature studies: Database searches vs. backward snowballing. In Proceedings of the 6th International Symposium on Empirical Software Engineering and Measurement, ESEM, Lund, Sweden, 19–21 September 2012; pp. 29–38.
48. Ceccotti, A. New Technologies for Construction of Medium-Rise Buildings in Seismic Regions: The XLAM Case. *Struct. Eng. Int.* **2008**, *18*, 156–165. [CrossRef]
49. van Eck, N.J.; Waltman, L. VOS: A New Method for Visualizing Similarities Between Objects. In *Advances in Data Analysis. Studies in Classification, Data Analysis, and Knowledge Organization*; Decker, R., Lenz, H.J., Eds.; Springer: Berlin/Heidelberg, Germany, 2017. [CrossRef]

50. Strauss, A.L.; Corbin, J.M. *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*; SAGE Publications: Thousand Oaks, CA, USA, 1998.
51. *EN 15978:2011*; Sustainability of Construction Works–Assessment of Environmental Performance of Buildings–Calculation Method. CEN-European Committee for Standardization: Brussels, Belgium, 2011.
52. Fasterholdt, I.; Lee, A.; Kidholm, K.; Yderstræde, K.B.; Pedersen, K.M. A qualitative exploration of early assessment of innovative medical technologies. *BMC Health Serv. Res.* **2018**, *18*, 837. [CrossRef]
53. Sandhaas, C.; Schädle, P.; Ceccotti, A. Innovative timber building systems: Comparative testing and modelling of earthquake behaviour. *Bull. Earthq. Eng.* **2018**, *16*, 1961–1985. [CrossRef]
54. Pei, S.; Popovski, M.; van de Lindt, J. Seismic design of a Multi-story cross laminated timber building based on componet level testing. In Proceedings of the 10th World Conference on Timber Engineering, Auckland, New Zealand, 15–19 July 2012.
55. Popovski, M.; Gavric, I. Performance of a 2-Story CLT House Subjected to Lateral Loads. *J. Struct. Eng.* **2016**, *142*, E4015006. [CrossRef]
56. Hashemi, A.; Masoudnia, R.; Quenneville, P. A numerical study of coupled timber walls with slip friction damping devices. *Constr. Build. Mater.* **2016**, *121*, 373–385. [CrossRef]
57. Polastri, A.; Giongio, I.; Piazza, M. An Innovative Connection System for Cross-Laminated Timber Structures. *Struct. Eng. Int.* **2017**, *27*, 502–511. [CrossRef]
58. Barbosa, A.R.; Rodrigues, L.G.; Sinha, A.; Higgins, C.; Zimmerman, R.B.; Breneman, S.; Pei, S.; van de Lindt, J.W.; Berman, J.; McDonnell, E. Shake-Table Experimental Testing and Performance of Topped and Untopped Cross-Laminated Timber Diaphragms. *J. Struct. Eng.* **2021**, *147*, 4021011. [CrossRef]
59. Zhong, Z.; Gou, Z. Adopting cross-laminated timber in architectural design to reduce embodied carbon emission in China based on the diffusion of innovation theory. *Build. Res. Inf.* **2023**, *51*, 834–852. [CrossRef]
60. Poirier, É.A.; Staub-French, S.; Pilon, A.; Fallahi, A.; Teshnizi, Z.; Tannert, T.; Froese, T. Design process innovation on brock commons tallwood house. *Constr. Innov. Inf. Process Manag.* **2021**, *22*, 23–40. [CrossRef]
61. Latour, M.; Rizzano, G. Cyclic behavior and modeling of a dissipative connector for Cross-Laminated Timber panel buildings. *J. Earthq. Eng.* **2014**, *19*, 137–171. [CrossRef]
62. Scotta, R.; Marchi, L.; Trutalli, D.; Pozza, L. A dissipative connector for CLT buildings: Concept, design and testing. *Materials* **2016**, *9*, 139. [CrossRef] [PubMed]
63. Polastri, A.; Giongo, I.; Angeli, A.; Brandner, R. Mechanical characterization of a pre-fabricated connection system for cross laminated timber structures in seismic regions. *Eng. Struct.* **2018**, *167*, 705–715. [CrossRef]
64. Trutalli, D.; Marchi, L.; Scotta, R.; Pozza, L. Capacity design of traditional and innovative ductile connections for earthquake-resistant CLT structures. *Bull. Earthq. Eng.* **2019**, *17*, 2115–2136. [CrossRef]
65. Fitzgerald, D.; Miller, T.; Sinha, A.; Nairn, J. Cross-laminated timber rocking walls with slip-friction connections. *Eng. Struct.* **2020**, *220*, 110973. [CrossRef]
66. Hashemi, A.; Zarnani, P.; Quenneville, P. Earthquake resistant timber panelised structures with resilient connections. *Structures* **2020**, *28*, 225–234. [CrossRef]
67. Moerman, B.; Li, M.; Smith, T.; Lim, H. Design and cyclic testing of bolted end plate connections between steel link beams and cross-laminated timber for coupled shear walls. *Constr. Build. Mater.* **2022**, *353*, 129060. [CrossRef]
68. Zhao, Y.; Yuan, Y.; Wang, C.; Zheng, J.; Zhou, Y. Experimental study on shear performance of steel-timber screw connectors with grout pockets. *Eng. Struct.* **2022**, *266*, 114535. [CrossRef]
69. Assadi, S.; Hashemi, A.; Quenneville, P. High performance rocking timber wall with innovative low-damage floor connections. *Structures* **2021**, *57*, 105075. [CrossRef]
70. Marchisella, A.; Muciaccia, G. A new hold-down device for seismic applications in CLT buildings: Design, testing, analytical and numerical assessment. *Eng. Struct.* **2024**, *318*, 118689. [CrossRef]
71. Longman, R.P.; Xu, Y.; Sun, Q.; Turkan, Y.; Riggio, M. Digital Twin for Monitoring In-Service Performance of Post-Tensioned Self-Centering Cross-Laminated Timber Shear Walls. *J. Comput. Civ. Eng.* **2023**, *37*, 4022055. [CrossRef]
72. Vilguts, A.; Phillips, A.; Jerves, R.; Antonopoulos, C.A.; Griechen, D. Monotonic testing of single shear-plane CLT-to-CLT joint with hardwood dowels. *J. Build. Eng.* **2024**, *88*, 109252. [CrossRef]
73. Buck, D.; Wang, X.; Hagman, O.; Gustafsson, A. Bending Properties of Cross Laminated Timber (CLT) with a 45° Alternating Layer Configuration. *BioResources* **2016**, *11*, 4633–4644. [CrossRef]
74. Sun, Q.; Huang, Q.; Duan, Z.; Zhang, A. Recycling Potential Comparison of Mass Timber Constructions and Concrete Buildings: A Case Study in China. *Sustainability* **2022**, *14*, 6174. [CrossRef]
75. Estrella, X.; Mureșan, A.; Brütting, J.; Redaelli, D.; Fivet, C. RE:SLAB—A load bearing system for open-ended component reuse in building structures. *Front. Built Environ.* **2024**, *10*, 1355445. [CrossRef]
76. Riggio, M.; Vedove, A.D.; Piazza, M. Load-bearing furniture modules for fast deployable and reusable systems. *Front. Built Environ.* **2024**, *10*, 1405500. [CrossRef]

77. Tesfamariam, S.; Stiemer, S.F.; Dickof, C.; Bezabeh, M.A. Seismic Vulnerability Assessment of Hybrid Steel-Timber Structure: Steel Moment-Resisting Frames with CLT Infill. *J. Earthq. Eng.* **2014**, *18*, 929–944. [CrossRef]
78. Marini, A.; Passoni, C.; Belleri, A.; Feroldi, F.; Preti, M.; Metelli, G.; Riva, P.; Giuriani, E.; Plizzari, G. Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: A proof of concept. *Eur. J. Environ. Civ. Eng.* **2017**, *26*, 2475–2495. [CrossRef]
79. Stazi, F.; Serpilli, M.; Maracchini, G.; Pavone, A. An experimental and numerical study on CLT panels used as infill shear walls for RC buildings retrofit. *Constr. Build. Mater.* **2019**, *211*, 605–616. [CrossRef]
80. Margani, G.; Evola, G.; Tardo, C.; Marino, E.M. Energy, Seismic, and Architectural Renovation of RC Framed Buildings with Prefabricated Timber Panels. *Sustainability* **2020**, *12*, 4845. [CrossRef]
81. Zanni, J.; Cademartori, S.; Marini, A.; Belleri, A.; Passoni, C.; Giuriani, E.; Riva, P.; Angi, B.; Brumana, G.; Marchetti, A.L. Integrated Deep Renovation of Existing Buildings with Prefabricated Shell Exoskeleton. *Sustainability* **2021**, *13*, 11287. [CrossRef]
82. Badini, L.; Ott, S.; Aondio, P.; Winter, S. Seismic strengthening of existing RC buildings with external cross-laminated timber (CLT) walls hosting an integrated energetic and architectural renovation. *Bull. Earthq. Eng.* **2022**, *20*, 5963–6006. [CrossRef]
83. Smiroldo, F.; Kallioras, S.; Sommacal, G.; Bournas, D.; Piazza, M.; Giongo, I. Full-scale testing of masonry-infilled RC frames retrofitted with cross-laminated timber panels. *Eng. Struct.* **2023**, *294*, 116789. [CrossRef]
84. Yang, T.Y.; Lepine-Lacroix, S.; Ramos Guerrero, J.; McFadden, J.B.W.; Al-Janabi, M.A.Q. Seismic performance evaluation of innovative balloon type CLT rocking shear walls. *Resilient Cities Struct.* **2022**, *1*, 44–52. [CrossRef]
85. Bolvardi, V.; Pei, S.; van de Lindt, J.W.; Dolan, J.D. Direct displacement design of tall cross laminated timber platform buildings with inter-story isolation. *Eng. Struct.* **2017**, *167*, 740–749. [CrossRef]
86. Hashemi, A.; Zarnani, P.; Masoudnia, R.; Pierre Quenneville, P. Seismic resilient lateral load resisting system for timber structures. *Constr. Build. Mater.* **2017**, *149*, 432–443. [CrossRef]
87. Ponzo, F.C.; Cesare, A.D.; Lamarucciola, N.; Nigro, D. Seismic Design and Testing of Post-tensioned Timber Buildings With Dissipative Bracing Systems. *Front. Built Environ.* **2019**, *5*, 104. [CrossRef]
88. Sun, X.; He, M.; Li, Z.; Lam, F. Seismic performance assessment of conventional CLT shear wall structures and post-tensioned CLT shear wall structures. *Eng. Struct.* **2019**, *196*, 109285. [CrossRef]
89. Chen, Z.; Popovski, M.; Iqbal, A. Structural performance of post-tensioned CLT shear walls with energy Dissipators. *J. Struct. Eng.* **2020**, *146*, 4020035. [CrossRef]
90. Carrero, T.; Montano, J.W.; Berwart, S.; María, H.S.; Guindos, P. Seismic Behavior of Innovative Hybrid CLT-steel Shear Wall for Mid-Rise Buildings. *Bull. Earthq. Eng.* **2021**, *19*, 5917–5951. [CrossRef]
91. Khajehpour, M.; Pan, Y.; Tannert, T. Seismic Analysis of Hybrid Steel Moment Frame CLT Shear Walls Structures. *J. Perform. Constr. Facil.* **2021**, *35*, 4021059. [CrossRef]
92. Matteoni, M.; Ciurlanti, J.; Bianchi, S.; Pampanin, S. Fragility functions for low-damage post-tensioned timber frames. *Earthq. Eng. Struct. Dyn.* **2024**, *53*, 4741–4762. [CrossRef]
93. Moerman, B.; Li, M.; Smith, T. Seismic Design of Hybrid Coupled CLT Shear Walls with Steel Link Beams. *Earthq. Eng. Struct. Dyn.* **2025**, *54*, 1520–1539. [CrossRef]
94. Araújo, G.; Simpson, B.; Barbosa, A.; Pieroni, L.; Ho, T.X.; Orozco O, G.F.; Miyamoto, B.T.; Sinha, A. Experimental and Numerical Simulation of a Three-Story Mass Timber Building with a Pivoting Wall and Buckling-Restrained Boundary Elements. *J. Struct. Eng.* **2025**, *151*, 4025089. [CrossRef]
95. Hashemi, A.; Lal, R. Seismic performance evaluation of mass timber buildings equipped with resilient and conventional friction devices. *Resilient Cities Struct.* **2025**, *4*, 103–115. [CrossRef]
96. Lal, R.; Hashemi, A.; Quenneville, P. An innovative connection system for platform-type mass timber buildings. *Resilient Cities Struct.* **2025**, *4*, 14–29. [CrossRef]
97. Wang, X.; He, M.; Li, Z. Experimental testing of platform-type and balloon-type cross-laminated timber (CLT) shear walls with supplemental energy dissipators. *J. Build. Eng.* **2023**, *66*, 105943. [CrossRef]
98. Tachibana, K.; Nagashima, T.; Pei, S.; Isoda, H.; Miyazaki, T.; Abe, S.; van de Lindt, J.W.; Pryor, S.E. Shake table test of a full-scale ten-story mass timber building designed with Japanese building standard law. *Eng. Struct.* **2025**, *343*, 120851. [CrossRef]
99. Loss, C.; Davison, B. Innovative composite steel-timber floors with prefabricated modular components. *Eng. Struct.* **2017**, *132*, 695–713. [CrossRef]
100. Ávila, F.; Dechent, P.; Opazo, A. Seismic behaviour evaluation of CLT horizontal diaphragms on hybrid buildings with reinforced concrete shear walls. *Eng. Struct.* **2021**, *244*, 112698. [CrossRef]
101. FEMA. *Seismic Performance Assessment of Buildings: Volume 1—Methodology*; FEMA, P-58-1; Applied Technology Council: Redwood City, CA, USA; Federal Emergency Management Agency: Washington, DC, USA, 2018. Available online: https://femap58.atcouncil.org/supporting-materials (accessed on 10 March 2025).
102. Ren, H.; Bahrami, A.; Cehlin, M.; Wallhagen, M. A state-of-the-art review on connection systems, rolling shear performance, and sustainability assessment of cross-laminated timber. *Eng. Struct.* **2024**, *317*, 118552. [CrossRef]

103. Federal Emergency Management Agency. FEMA P695. In *Quantification of Building Seismic Performance Factors*; Federal Emergency Management Agency: Washington, DC, USA, 2009.
104. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]