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Connection Systems for Modular Cross-Laminated Timber Structures: A PRISMA Systematic Review of Typologies, Seismic Performance, and Circularity Trade-Offs

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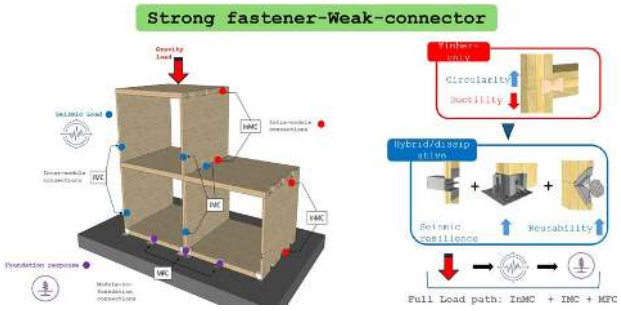
Abstract

Modular cross-laminated timber (CLT) construction offers rapid, low-carbon housing, yet its seismic viability is governed by connection performance. This PRISMA-based systematic review of 50 publications compares the mechanical characterization of twenty connection systems for volumetric CLT across the complete load path, intra-module (InMC), inter-module (IMC) and module-to-foundation (MFC), and sets it against reusability. The evidence separates two families. Adhesive-free, timber-only interlocking joints support circularity but dissipate energy through irreversible timber crushing, so their cyclic ductility is limited and non-repeatable, whereas hybrid steel-timber systems and friction dampers concentrate damage in replaceable components and give stable, repeatable hysteresis; together they define a damage-avoidance hierarchy. Full-scale validation remains scarce, durability unquantified, and the available data biased toward moderate-seismicity codes. The way forward is strong fastener-weak connector design, with stiffness-compatibility guidelines that treat InMC, IMC and MFC as one system.

Keywords

Connections; cross-laminated timber; modular construction; industrialized construction; circularity; sustainability

Graphical abstract



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ABBREVIATIONS
The following abbreviations are used in this manuscript:
DfMA Design for Manufacturing and Assembly
DfD Design for Disassembly
DW Densified Wood
CLT Cross-Laminated Timber
IMC Inter-Module Connection
InMC Intra-Module Connection
MFC Module-to-Foundation Connection
FEM Finite Element Modeling
CNC Computer Numerical Control
STS Self-Tapping Screw
RPF Rotational Press-Fit
LVL Laminated Veneer Lumber
MOE Modulus of Elasticity

1 INTRODUCTION

The construction sector accounts for approximately 34% of global energy consumption and 37% of greenhouse-gas emissions, with 28% attributable to building operations and 11% to material production and construction processes (UNEP, 2025). This footprint is largely driven by carbon-intensive materials such as concrete and steel (Chastas et al., 2017). This is especially true in seismic regions, where reinforced concrete, structural steel, and steel–concrete composite systems remain the predominant structural solutions for medium- and high-rise buildings.

Reducing embodied emissions through timber, when combined with appropriate design, resilience criteria and a whole-life-carbon approach, can also lower operational emissions (UNEP, 2025). Simultaneously, global housing demand is growing under increasing natural hazard exposure and urban densification (Cole et al., 2008; UNEP, 2025), creating an urgent need for construction systems that are sustainable, resilient and resource-efficient (Schulte et al., 2023; Shufrin et al., 2023), but also capable of meeting the stringent structural and safety requirements of seismic regions.

Cross-laminated timber (CLT) has emerged over the last few decades as a promising construction system for medium- and high-rise buildings as well as long-span structures by balancing cost efficiency, design flexibility, and structural resilience (Liu and Fischer, 2022; Sandoli et al., 2021). It is an engineered mass timber product manufactured by laminating layers of timber boards in alternating orthogonal directions, resulting in large structural panels with enhanced strength, stiffness, dimensional stability, and bidirectional load-bearing capacity. These characteristics enable CLT panels to function as load-bearing walls, floors, roofs, and complete structural systems as well as adaptability to emerging design philosophies, such as disassemblable systems (Ottenhaus et al., 2023; Tenório et al., 2024). In addition to their excellent structural performance and seismic resistance, CLT buildings offer significant environmental benefits through reduced embodied carbon, rapid prefabrication, and a high degree of design flexibility. It makes a substantial contribution to carbon sequestration, achieved through intensive timber use and reduced waste in prefabrication processes. Prefabrication and dry-assembly methods further improve construction efficiency and quality, offering enhanced sustainability, rapid deployment, and adaptability to post-disaster contexts (Bhandari et al., 2023a), while supporting circular economy strategies through disassembly and reuse (Bhandari et al., 2023a; Tenório et al., 2024; Ottenhaus et al., 2023).

Research on CLT is increasingly organized around a triad of critical aspects: connection systems, material performance, and comprehensive sustainability assessments (Ren et al., 2024a). This focus is particularly relevant in seismic regions, where alternative low-carbon solutions capable of meeting stringent seismic demands are urgently needed. The maturation of CLT technology, together with the growing demand for sustainable and rapidly deployable housing, has fostered the development of modular CLT construction (Blismas et al., 2012), in which structural performance depends not only on the mechanical properties of the panels but also on the efficiency and reliability of the connections between modules. Consequently, the design of connection systems has become a critical determinant of the safety, robustness, and seismic resilience of modular CLT buildings (Bhandari et al., 2023a; Liu and Fischer, 2022; Sandoli et al., 2021).

Of that triad, material performance rests on the mechanical properties of wood, which depend on the species and remain highly variable within a species and even within a single visual grade. For graded lumber, Yang et al. (2008) report static bending moduli of 7.3 to 20.8 GPa in Douglas-fir and 8.0 to 16.4 GPa in Japanese cedar, with coefficients of variation of 10 to 23% within each grade, and show that density alone does not predict them reliably; across hardwood and softwood species, compressive strength ranges from 24.8 to 69.5 MPa in the compilation of Verma et al. (2014). Structural use therefore requires assignment to strength classes from the characteristic values of bending strength, density and mean modulus of elasticity, EN 338 (2016) for solid timber and EN 14080 (2013) for glued laminated timber,

and the class is governed by the least favorable of the three: an Iroko population with a characteristic bending strength of 71.7 MPa and a characteristic density of 553 kg/m3 was assigned to class D40 (Bucci et al., 2017). Lamination and hybridization reduce this scatter but add variability at the bond line and at the joints: in Iroko laminates, scarf joints reduced the characteristic bending strength by 33% while leaving the bending and shear moduli unchanged (Corigliano et al., 2017); in laminated bamboo composites, cross-plied lay-ups lowered the flexural strength by about 18% relative to parallel lay-ups (Verma et al., 2014); and in FRP-repaired wood piles the load-transfer detail between wood and composite, rather than the wood, governed the restored capacity (Lopez-Anido et al., 2003). A summary of these experimental investigations is given in Table A3 of Appendix A. Connection performance is therefore always measured on a specific base material (Section 4.2), so cross-study comparisons of connection strength and stiffness inherit the variability of the timber in addition to that of the connector.

Material performance is also a bonding question. CLT, like the other engineered wood products, is bonded with petroleum-derived synthetic thermosetting adhesives, formaldehyde-based resins, isocyanates and polyurethanes (Kumar and Leggate, 2022), so that a material valued as green is assembled with a fossil-derived bond line that raises formaldehyde-emission concerns and ties the product to petrochemical supply (Hemmilä et al., 2017). The literature responds along two tracks. The first replaces the synthetic resin with bio-based adhesives derived from lignin, tannin, protein or starch: they reduce formaldehyde and volatile emissions and the dependence on fossil raw materials, but their water resistance and strength still confine them mainly to non-structural products, and adhesives for structural and exterior use remain under development (Pizzi, 2016; Hemmilä et al., 2017; Kumar and Leggate, 2022). The second removes the adhesive from the joint: dowel-laminated and densified-wood products (Sotayo et al., 2020) and adhesive-free connectors for CLT (Ren et al., 2024a) transfer load through geometric interlocking and wood-to-wood contact rather than through a resin. The second track is the one this review meets: the timber-only interlocking connections examined here remove the adhesive from the connection, if not from the panel, so that eliminating the resin is at once a circularity strategy and a shift of the failure mode into the timber, the trade-off analyzed in Section 4.3.

1.1 The significance of connections in CLT buildings

Panelized CLT structures rely on high in-plane stiffness to act as both shear walls and diaphragms, interconnected through mechanical fasteners and metal connectors (Ceccotti et al., 2013; Gonzalez et al., 2018; Lal et al., 2025; Yasumura et al., 2016; Izzi et al., 2018a). Conventional CLT connections include self-tapping screws (STS), splines and stitchings, angle brackets, metallic straps, hold-downs and bolted connections. Under seismic demand, mechanical connections constitute the primary source of energy dissipation, following an established hierarchy in which energy dissipation concentrates in shear-wall-to-shear-wall parallel connections (Izzi et al., 2018b), followed by hold-downs resisting overturning demands and angle brackets preventing sliding (Izzi et al., 2018a; Popovski and Gavric, 2016). This hierarchy can only be mobilized if connection detailing is carefully addressed; otherwise, brittle failure modes may govern under extreme seismic loading (Popovski and Gavric, 2016). Ductility and energy dissipation in the connections are necessary but insufficient to guarantee minimal damage to CLT components; connections must also promote ductile failure modes, accommodate interaction effects (e.g., uplift–lateral force combinations), and mitigate fastener-group effects (Fragiacomo et al., 2011; Pozza et al., 2018). Monotonic, cyclic and shake-table testing has shown that well-designed conventional CLT connections retain strength and stiffness under seismic demands (Ceccotti et al., 2013; Yasumura et al., 2016; Popovski and Gavric, 2016; Ceccotti, 2008; Hughes et al., 2019), while CLT panels themselves remain largely linear-elastic (Pozza et al., 2014).

1.2 Challenges and research gaps for seismic-resilient connections in modular CLT structures

Most existing modular CLT buildings are concentrated in low-seismicity regions of Europe and North America (Bhandari et al., 2023a; Zambrano-Jaramillo and Fischer, 2026), although CLT's favorable strength-to-weight ratio and comparatively lower inertial forces have stimulated interest in its use in seismically active areas facing urgent housing demand (Sandoli et al., 2021; Dong et al., 2020; van de Lindt et al., 2019). There is significant potential for advancing seismic-resilient modular CLT systems either by enhancing and adapting conventional connections to modular applications or by developing novel modular-specific connection technologies. Innovations should address the geometry and installation constraints that limit accessibility, characterization and reliability of these connections (Boafo et al., 2016; Li and Tsavdaridis, 2023a; Rajanayagam et al., 2021); establishing reliable stiffness and strength requirements (Fragiacomo et al., 2011); incorporating box-like action and multi-directional load transfer into numerical models (Liu et al., 2025; Brown et al., 2021; D'Arenzo et al., 2024; Mallardi et al., 2025; Ruggeri et al., 2022); avoiding improper failure modes such as wood splitting and fastener pull-out through targeted over-strengthening and calibrated design factors (Sandoli et al., 2021; Izzi et al., 2018b; Tamagnone et al., 2020; Bhandari et al., 2023b); and, from a resilience perspective, concentrating damage in the connector rather than in the timber members (van de Lindt et al., 2019).

Innovation must additionally address circular construction through connections that improve sustainability, disassembly and constructability (Bhandari et al., 2023a; Arnette et al., 2014; Cottafava and Ritzen, 2021; Ren et al., 2024b; Ottenhaus et al., 2023).

Despite significant progress in connector innovation (Li et al., 2024; Li et al., 2021) and computational modeling (Bhandari et al., 2023a; Bhandari et al., 2023b; Xu et al., 2024), the knowledge base on modular CLT connections remains fragmented (Tenório et al., 2024). Several recent reviews have advanced it from complementary angles. Bhandari et al. (2023a) reviewed 122 modular CLT buildings completed between 2005 and 2021 in terms of design, manufacturing and logistics, and their implications for temporary housing in seismic regions. They classified connections as intra-module, inter-module and module-to-foundation, following Rajanayagam et al. (2021), but found the connection systems of most projects poorly documented. They identified connections that combine rapid deployment with reusability, characterized under lateral and cyclic loading, as the most urgent research gap. Ren et al. (2024a) reviewed connection systems, material performance and sustainability assessment of CLT for panelized construction, without addressing modular CLT structures. Ottenhaus et al. (2023) reviewed disassemblable timber connection systems for adaptability, disassembly and reuse; they assessed reversibility qualitatively for timber connections in general and stated that reuse requires damage to be concentrated in a replaceable fuse while the remaining components are capacity-protected. Two recent reviews are closer to the present work. Heidari et al. (2025) aggregate the mechanical performance of CLT connections into a comprehensive design database of 522 connection sets and 2,048 test specimens, but characterize joinery at the connection and assembly level and are oriented to panelized systems. Zambrano-Jaramillo and Fischer (2026) review inter-modular connections for volumetric CLT, scoring seven representative systems against a multi-criteria set of structural, manufacturing, construction, and experimental and numerical objectives; they explicitly consider demountability and reuse and map built volumetric CLT projects against seismic and wind hazard. Both are valuable, but their scope stops short of the modular load path as a whole. The former remains at the component and assembly level for panelized construction; the latter is confined to the inter-modular interface and mentions intra-module connections only in passing. As a result, the interaction between a module's internal stiffness and the complete load path, under the cyclic demands of high-seismic regions, remains largely unaddressed. The aim of this review is therefore to compile and compare the mechanical characterization of the connection systems reported for modular CLT structures across the entire load path, intra-module (InMC), inter-module (IMC) and module-to-foundation (MFC) connections, and to set it against their compatibility with disassembly and reuse. Such a comparison is timely: the two reviews just discussed appeared in 2025 and 2026, so the evidence on panelized and on inter-modular connections has only now been consolidated, while the seismically active regions that most need rapidly deployable housing still design with performance data generated in moderate-seismicity contexts.

1.3 Contribution relative to prior reviews

The present review is narrower than the closest prior reviews in several respects and makes no claim of breadth: Heidari et al. (2025) compile roughly an order of magnitude more mechanical test data, Zambrano-Jaramillo and Fischer (2026) also cover wind hazard, and Bhandari et al. (2023a) cover the design, manufacturing and logistics of built projects (a criterion-by-criterion comparison is given in Table A1 of Appendix A). It differs from these three, and from the broader reviews of Ren et al. (2024a) and Ottenhaus et al. (2023), in the question it asks of the evidence. It adopts the intra-module, inter-module and module-to-foundation classification of the modular-building literature (Rajanayagam et al., 2021; Bhandari et al., 2023a) as the frame for compiling and comparing the mechanical characterization of connections, and treats the three as one load path. Prior reviews with mechanical data remain at the connection and assembly level for panelized systems (Heidari et al., 2025) or at the inter-modular interface (Zambrano-Jaramillo and Fischer, 2026); the review that names all three classes describes them from built projects, without mechanical characterization (Bhandari et al., 2023a). Along that load path, the present review sets quantitative cyclic data against reusability, rather than assessing circularity qualitatively or leaving it aside.

Its central argument is that a connection's capacity to support circularity is fundamentally constrained by its damage-avoidance capacity. This is the principle that Ottenhaus et al. (2023) state for timber connections in general, and that underlies the connection-resilience criterion of Zambrano-Jaramillo and Fischer (2026). The present review tests it against the compiled cyclic data of modular connections. On that basis it identifies the damage-avoidance hierarchy (Section 4.2.3) that ranks the reviewed connections by reusability and shows which of them achieve seismic safety and modular reusability simultaneously. In doing so it addresses the gap that Bhandari et al. (2023a) identified as the most urgent for modular CLT: connections that combine rapid deployment with reusability, characterized under lateral and cyclic loading. Unlike the reviews above, the corpus is assembled under a reported PRISMA protocol, and the analysis identifies a normative bias in the available performance data toward moderate-seismicity European codes, which limits transferability to subduction-zone regimes (Sections 4.1.1 and 4.4.4).

1.4 Research questions

To address this gap, the present systematic review is organized around four research questions (RQ):
RQ1. What is the current state of development of connection systems for modular CLT structures, and how can these systems be functionally classified according to their structural role?
RQ2. How do different connection technologies affect the mechanical performance of modular CLT structures, and how suitable are they for seismic applications?
RQ3. What trade-offs arise between designing modular CLT structures for circularity and meeting the requirements for seismic resilience, reuse and reusability?
RQ4. What are the main knowledge gaps in the current literature, and which research priorities should be addressed to support the standardization and wider adoption of modular CLT structures?

2 SCOPE

This review covers connection systems for volumetric modular CLT structures, organized by their position in the load path: intra-module, inter-module and module-to-foundation connections. It analyzes 50 publications selected through a systematic search based on the PRISMA guidelines, from which twenty connection systems with reported mechanical characterization were extracted. For each of them the review compiles geometry, materials, fasteners and failure modes, together with the mechanical results and the test conditions under which they were obtained, and on that basis evaluates seismic suitability and compatibility with disassembly and reuse. The bibliometric analysis is used to identify sources of bias in the evidence rather than as a finding in itself. Systems whose only evidence is conceptual or numerical are inventoried but not compared quantitatively, with the exception of C14, whose numerical results are reported for completeness. Connections conceived for panelized CLT are included only where the source studies propose or test them for modular use. Grey literature was excluded, so the findings are more representative of academic than industry practice. Finally, the review outlines the main knowledge gaps and research priorities for the standardization and wider adoption of modular CLT structures.

3 METHODOLOGY

The state of development in this field was assessed through a systematic review following the PRISMA guidelines (Page et al., 2021; Tsafnat et al., 2014). The initial database selection included Scopus, Web of Science and Wiley Online Library — recognized for their quality standards and broad disciplinary coverage — complemented by Google Scholar and ScienceDirect to mitigate the substantial overlap that has been documented between the primary databases (Pranckutė, 2021). Data were then extracted from the selected databases through an iterative search process, applying predefined search criteria to ensure consistency and reliability across platforms. Figure 1 presents the simplified PRISMA flow diagram of the study.

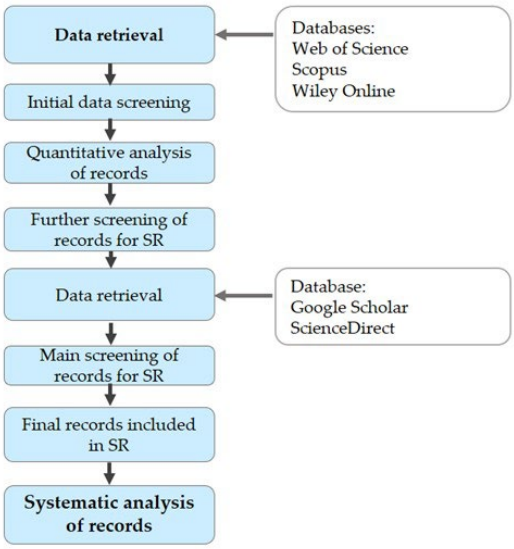


Figure 1. Simplified PRISMA flow diagram of the study.

The search strategy was built around the central theme of "connections for modular CLT structures". Keywords were defined prior to screening and were not modified during the review. Groups of search terms captured (i) connections and joints, (ii) modular, volumetric, industrialized and prefabricated CLT, and (iii) broader construction and off-site terms (see Table 1).

Table 1. Keywords used for database search and filtering.

Keywords	Connections for Modular CLT structures
General inclusion criteria	“connection” (or “joints”) and “modular” and “CLT” (or “timber”)
Set of specific keywords	“modular construction”, “modular building”, “prefabricated construction”, “industrialized construction”, ”volumetric structure” “off-site construction”, “mass timber”

Queries were built with the AND operator (e.g. "connection" AND "modular construction" AND "CLT"), with minor input adjustments across databases. The language filter was set to English. The queries returned 205 publications.

VOSviewer 1.6.20 (Van Eck and Waltman, 2010) was used to remove duplicates and to visualize bibliometric networks; the connected publications were clustered into three thematic groups, yielding a screened dataset of 142 publications (Figure 2). Searches were repeated between January and September 2025. The remaining 63 records were screened against three eligibility criteria (Reasons 1–3): inaccessible full text, off-topic abstract, and off-topic full text. Selection was performed by the first author and validated by the second and third. Backward and forward snowballing following Wohlin et al. (2022) added 14 studies not indexed in the primary databases. The final corpus comprised 50 articles.

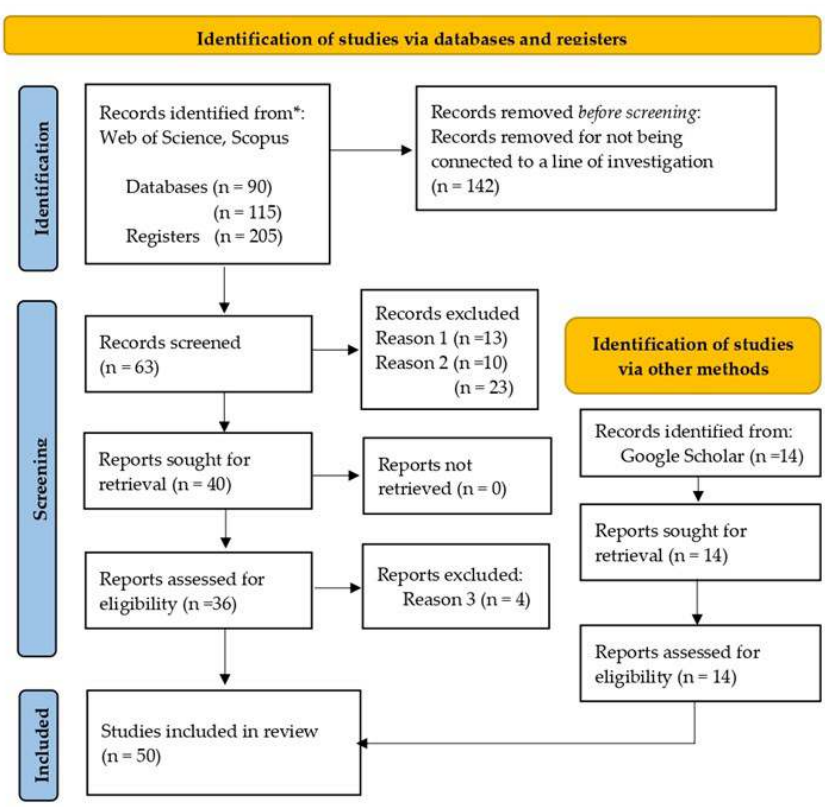


Figure 2. PRISMA 2020 flow diagram for new systematic reviews.

VOSviewer was subsequently used for author-, institution- and country-level co-authorship analysis to identify potential data bias. Each article was reviewed to extract technical information (mechanical principles, failure mechanisms, engineering properties). Studies were grouped into (i) experimental or numerical mechanical characterization and (ii) conceptual or design-oriented developments, and their data were compiled into summary tables (geometry, materials, fasteners, failure modes). A narrative synthesis integrated the evidence, highlighting the most significant findings, methodological approaches and conceptual contributions.

3.1 Methodological limitations of the systematic review process

Some relevant publications were inaccessible due to subscription restrictions and paywalls, and others were excluded because they were published in languages not covered by this review. Although snowballing was applied, the same eligibility criteria were enforced throughout to maintain PRISMA reproducibility. Grey literature was excluded, so findings may be more representative of academic than industry practice.

4 RESULTS

The Results are organized by research question. Section 4.1 addresses RQ1 (state of development and functional classification), Section 4.2 addresses RQ2 (mechanical performance and seismic suitability), Section 4.3 addresses RQ3 (circularity vs. seismic-resilience trade-offs), and Section 4.4 addresses RQ4 (knowledge gaps and research priorities).

4.1 Current state of development and functional classification of connection systems (RQ1)

4.1.1 Bibliometric snapshot of the field

The literature network built from the search results (Figure 3) is organized into three thematic subfields: a red cluster on modular construction, sustainability, circularity, interlocking mechanisms and innovative connectors; a green cluster on structural engineering, seismic performance and hybrid floor systems; and a blue cluster on numerical modeling and innovative connection systems, partly overlapping with the modular-construction theme.

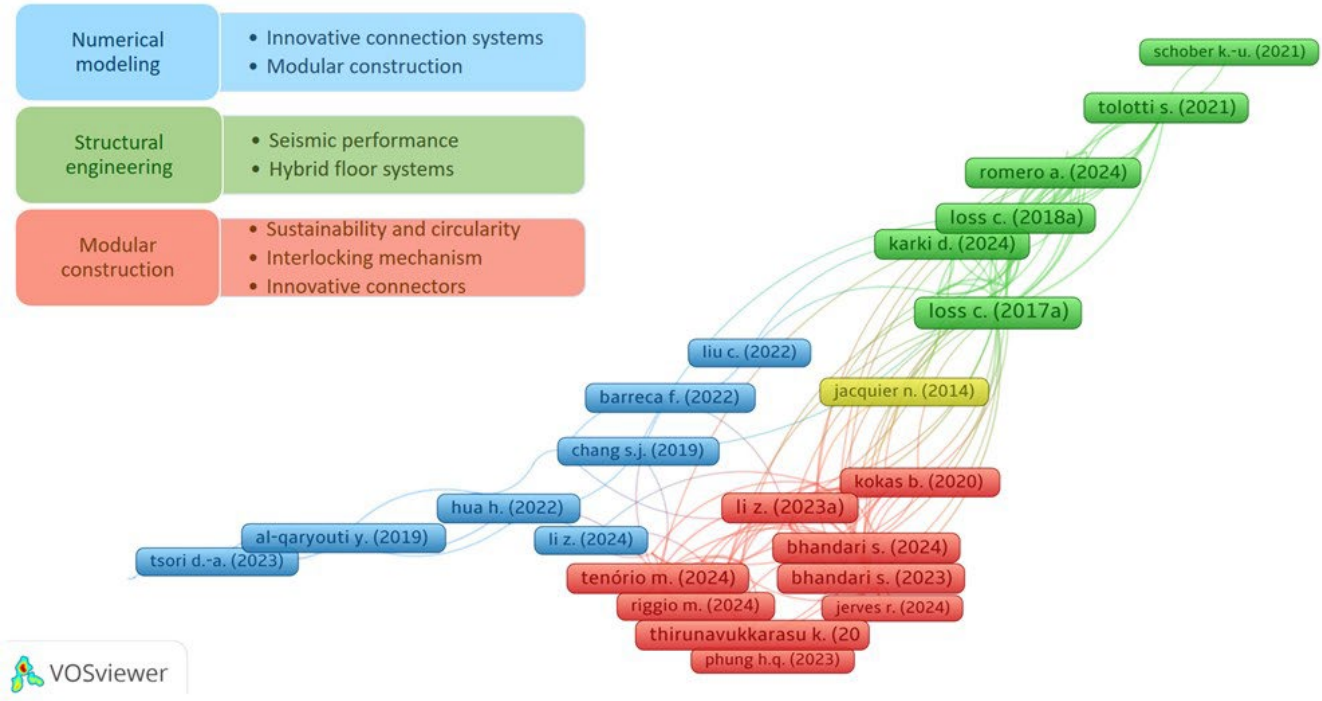


Figure 3. Thematic cluster analysis of research on modular CLT connections with VOSviewer.

The co-authorship analysis identified 163 authors distributed across 33 clusters, of which only 15 authors have more than two publications, forming six distinct clusters (Figure 4).

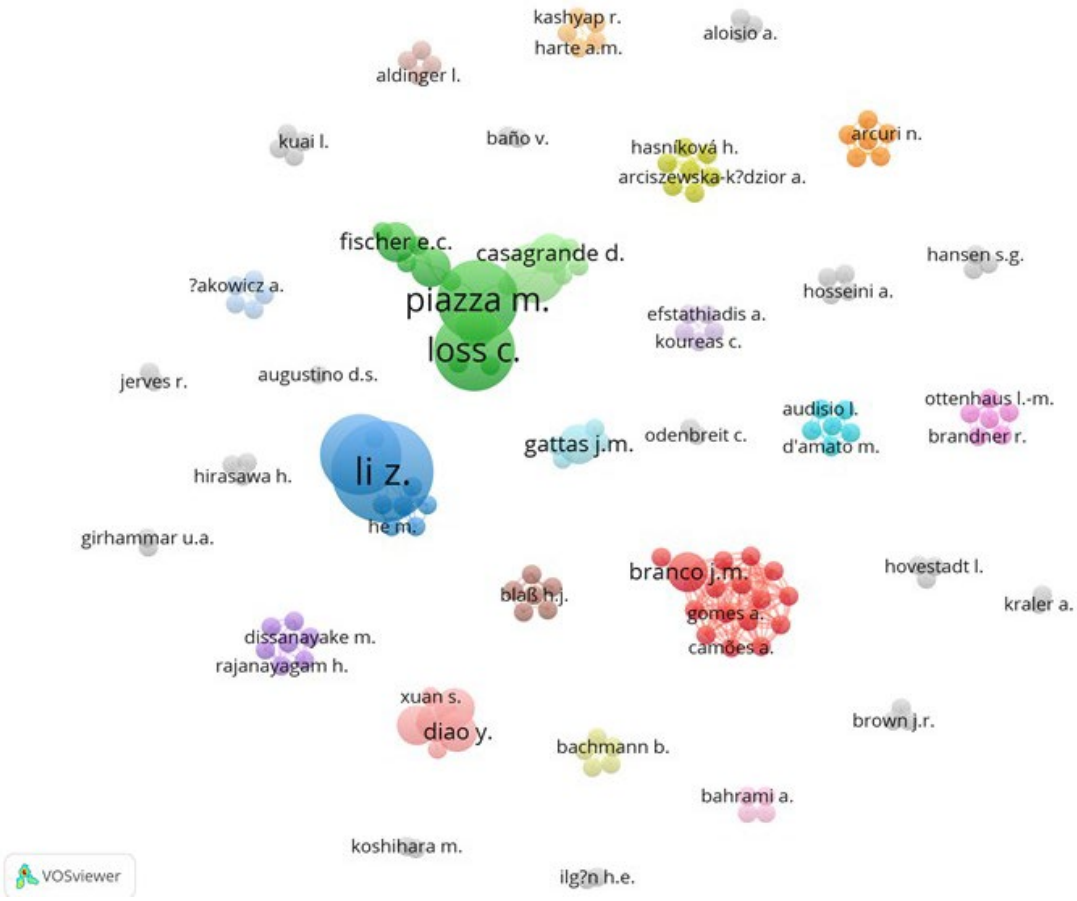


Figure 4. Co-authorship network and key research clusters.

The most productive authors are Zhengyao Li (5 papers) and Konstantinos Daniel Tsavdaridis (4 papers) in Cluster 3, and Cristiano Loss (4 papers) and Maurizio Piazza (4 papers) in Cluster 2; the latter two are also the most cited, with 515 and 345 citations respectively. Contributions come from 27 countries (Figure 5), with a strong concentration in Italy, the United Kingdom, China and the United States.

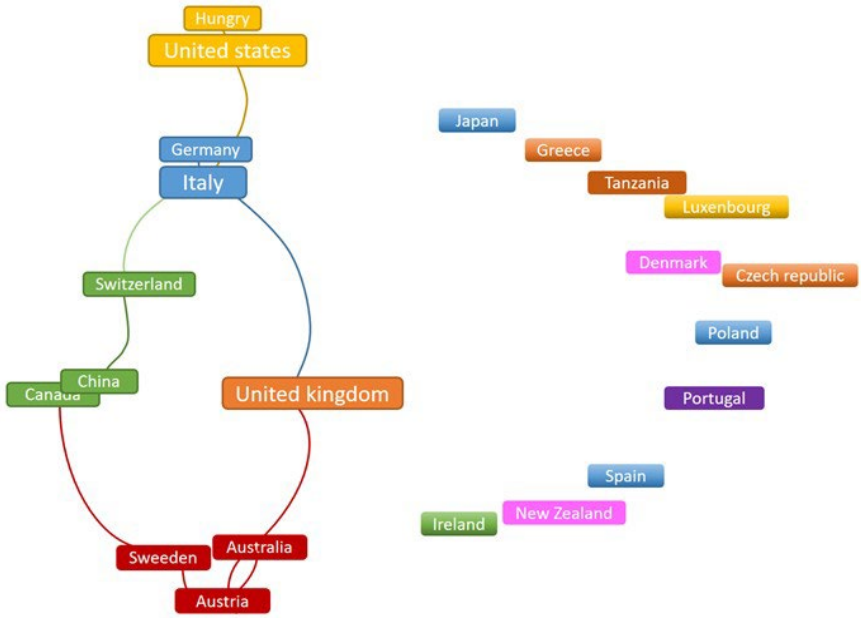


Figure 5. Country-level co-authorship and geographic distribution of research.

Scientific collaboration is therefore highly segmented: productive research nuclei form relatively closed clusters, with intense internal circulation of ideas and limited external exchange. This is compounded by a normative bias: connection development and testing are largely aligned with local standards, particularly Eurocode 8 (2004), so that reported performance data (inter-storey drift limits, ductility factors, stiffness degradation) are optimized for the moderate seismicity typical of European regions rather than for the extreme demands of subduction zones. This limits direct transferability to countries such as Chile, Japan or Peru, whose codes (NCh 433, 2009; NTE E.030, 2016; Building Standard Law, 1950) impose stricter drift limits and require higher energy-dissipation capacities.

4.1.2 Functional taxonomy: InMC, IMC and MFC

The performance of modular CLT structures is governed by their connections, and research has increasingly focused on advanced connection strategies that build upon established technologies — STS, metal-plate designs targeting specific energy-dissipation mechanisms (Araya et al., 2022), shear-key connectors and geometrically interlocking mechanisms. These technologies reflect a shift from the conventional "strong plate–weak fastener" concept toward a "strong fastener–weak metal connector" approach in which replaceable steel components act as structural fuses (Bhandari et al., 2023a; Polastri and Casagrande, 2022; Gao et al., 2023), concentrating plastic deformation in these elements and reducing damage to CLT panels (Gao et al., 2023; Li and Tsavdaridis, 2023b). For this hierarchy to be reliable, the fasteners and surrounding timber must be capacity-protected so that they remain elastic when the connector reaches its overstrength-amplified yield force; that is, the fastener-to-timber capacity must exceed the fully yielded connector resistance. This is the fuse-plus-capacity-protection arrangement that Ottenhaus et al. (2023) identify as the condition for reversible timber connections. Here "weak" denotes the component designed to yield first in a controlled, ductile manner, not one of lower ultimate strength.

Translating this into global structural performance requires defining the hierarchy of connections that establish the load path to the foundation. Compared to panelized systems, in CLT modules the role of connections is more critical, since fastening shifts from distributed lines to concentrated joints that govern efficiency and cyclic response. Three functional classes, adopted from the modular-building literature (Rajanayagam et al., 2021; Bhandari et al., 2023a) and applied here as the frame for the mechanical evidence, are used throughout (Figure 6):

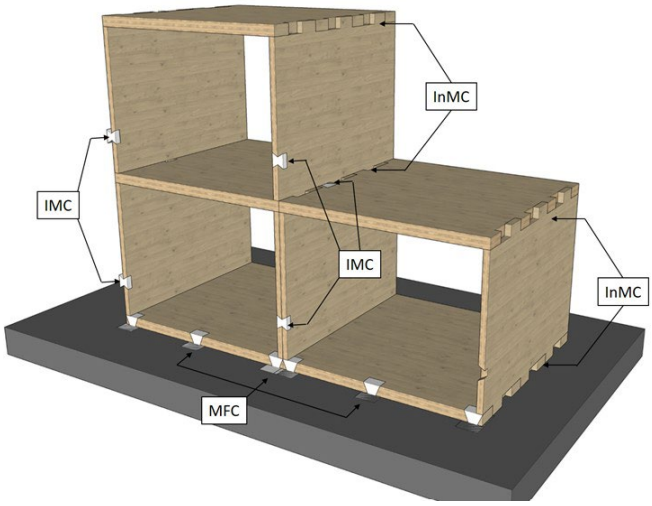


Figure 6. Modular structure connections: InMC, IMC and MFC.

- Intra-Module connections establish each module's internal structural integrity at its wall-to-wall, wall-to-floor and floor-to-floor interfaces, enabling the module to act as a coherent box; they therefore govern the module's racking stiffness and internal force distribution under service and seismic load, in addition to stabilizing it during transport and assembly.
- Inter-Module connections collect lateral loads, ensure horizontal diaphragm action and transfer forces vertically between stories, operating at module-to-module interfaces horizontally and vertically (Zambrano-Jaramillo and Fischer, 2026; Li et al., 2024; Lacey et al., 2018; Srisangeerthanan et al., 2018).
- Module-to-Foundation connections transmit both gravity and lateral loads and are placed at horizontal and vertical module interfaces with the foundation or concrete cores (Li et al., 2024; Lacey et al., 2018; Srisangeerthanan et al., 2018).

The location and detailing of IMC critically influence the building's lateral stiffness and its diaphragm classification (rigid, semi-rigid or flexible per ASCE 7 (2022)) and therefore its seismic response; inadequate IMC stiffness amplifies inter-storey drifts (Zambrano-Jaramillo and Fischer, 2026; Srisangeerthanan et al., 2018). Because the specific placement of IMC in floors, roofs or shear walls directly affects force distribution, variations in joint configuration can alter shear and moment demands on gravity columns by more than 60% (Lacey et al., 2018). Contemporary connection design is also governed by sustainability and circularity, driving innovation toward deconstructable systems compatible with Design for Disassembly (DfD), Design for Manufacturing and Assembly (DfMA) (Arnette et al., 2014; Cottafava and Ritzen, 2021) and reuse philosophies (Ottenhaus et al., 2023; Li et al., 2024). This taxonomy provides the basis for evaluating connections not only by capacity but also by structural role, damage-localization strategy and compatibility with modular constraints.

4.1.3 Typologies and mechanisms of modular connections

The reviewed connections (Table 2) are grouped by their mechanical load-transfer strategy: surface-based fastening, geometric interlocking and energy dissipation. Most were originally conceived for panelized configurations, so their use in modular CLT requires case-specific adaptation (Bhandari et al., 2023a).

Table 2. General overview of connections.

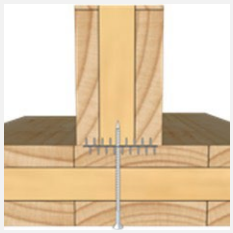
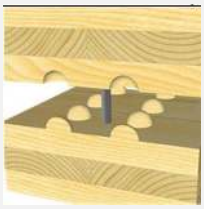
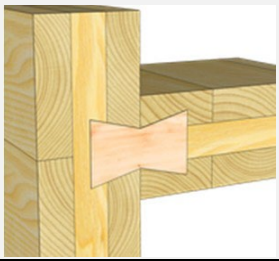
Connection name/Description	Connection figure	Materials	Reference
Wall-to-wall connections types			
C1 - Double sided nail plate: Uses a metal plate with an inclined STS to create a shear connection for CLT panels. Configurations M1 to M8 (see Table 3) change geometry and fastener distribution.		CLT in 20 mm layers with a total thickness of 60 mm, elaborated on C24 class timber according to ETA-8/0271. Double-sided punched metal plate of zinc coated steel 1.3 mm thickness with 6.5 and 8.2 mm screws.	(Jacquier and Girhammar, 2014)
C2 - Reversible connection: Self aligning connection with enhanced shear capacity		Eastern white pine timber C24. Steel bolts, M4 A2- 70 bolts.	(Hansen et al., 2021)
C3 - Metal dovetail: the metal dovetail contains a steel mortise and tenon part, which are fastened to the CLT panels by STS.		Grade C24 CLT panel. Steel connector with yielding strength 235 MPa STS (Rothoblaas HBS ⌀5×100 mm)	(Li et al., 2021)
C4 – Slot: Stiff connector inserted into grooves in the edges of CLT panels, creating a stiff vertical joint that allows multi panels walls to act as single unit to resist lateral loads.		Three and five layered CLT with grade C24 timber. Shear key in aluminum grade EN AW-6005A STS ⌀6x70 mm and 8x100 mm	(Polastri and Casagrande, 2022)
C5 - Non metallic double dovetail: LVL double dovetail connection for perpendicular CLT walls		Western Hemlock lumber 3 layered CLT with Grade E2. LVL made from fast-growing Chinese eucalyptus	(Gao et al., 2023)

Table 2. Continued...

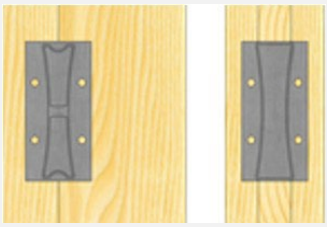
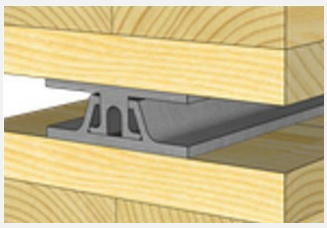
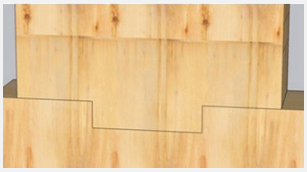
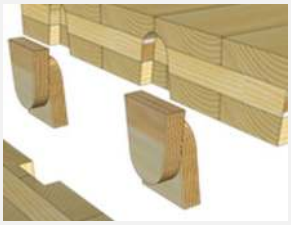
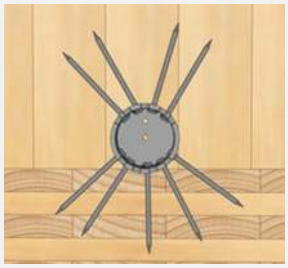
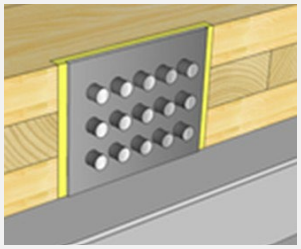
Connection name/Description	Connection figure	Materials	Reference
C6 - Interlocking shear: connector: Connection for lateral displacement with controlled deformation in the male connector		Five ply CLT grade GL24h Metallic alloy SS420/BR for the 3D printed steel connector. Fasteners: HBSP12120 screws	(Li and Tsavdaridis, 2023a)
C7 - Interlocking tension connector: Connection for perpendicular displacement with controlled deformation in the male connector		Five ply CLT grade GL24h Metallic alloy SS420/BR for the 3D printed steel connector. Fasteners: LBS7100 screws	(Li and Tsavdaridis, 2023a)
C8 - Non metallic dovetail: CLT dovetail joint for perpendicular CLT walls. Considering 3 tenon widths 70mm, 84mm, 105mm.		CLT in 35 mm layers with a total thickness of 105 mm, elaborated on Canadian No.2 grade hemlock lumber.	(Xu et al., 2024)
Wall to floor connection types			
C9 - Castellated joint: Rectangular mortise and tenon joint with matching parallel layers between both parts of the CLT connections.		Douglas fir timber CLT MOE parallel: 8000 MPa G0: 533 Grs: 53 Compressive strength: 18 MPa Shear strength: 3.39 MPa	(Brown et al., 2021)
C10 - Double dovetail: Connects wall to ceiling, transferring load though the shape with multiple levels for controlled deformation and ductile failure modes.		GL24h beams according to EN 14080. Connector made CNC machined LVL from wood-base material KetroQ .	(Pomaroli and Kraler, 2023)
C11 – Ring: Is a multi directional system, for connections timber to timber and timber to concrete elements. The ring uses screws to transfers loads between CLT panels, or bolted joints between rings.		Steel grade S275 and S355. Five layer CLT with reported density and moisture around 480 kg/m3 and 11.6%. Fasteners: LBSH ⌀7x200mm screws and 10.9 M16 steel bolts	(Fanti et al., 2025)
Floor connections			
C12 - Beam to panel : T1 are steel plates welded to the beam, connected with STS to the CLT. T2 Steel plates welded to steel beam connected to the CLT using epoxy based resin. T3 are T1 connections with the use of epoxy based resin.		CLT in 20 mm layers with a total thickness of 100 mm, elaborated on C24 class timber according to EN 338. HE-shaped steel beams S275 according to EN 10025. Epoxy-based resin.	(Loss et al., 2016a)

Table 2. Continued...

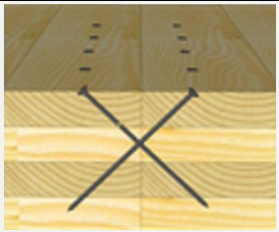
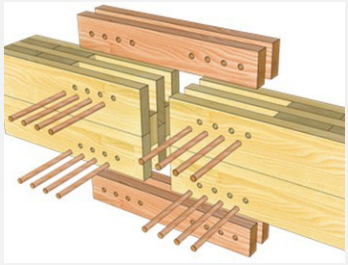
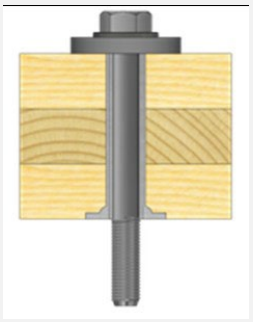
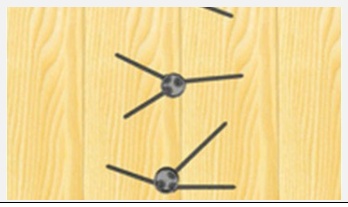
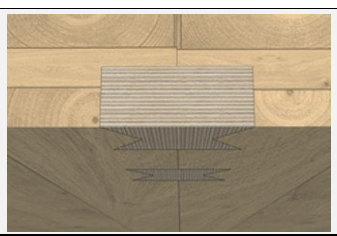
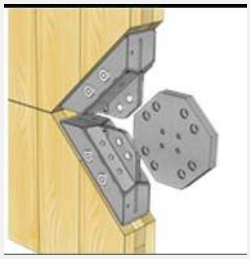
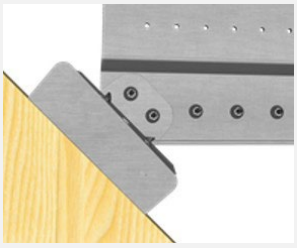
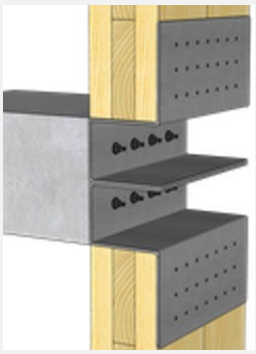
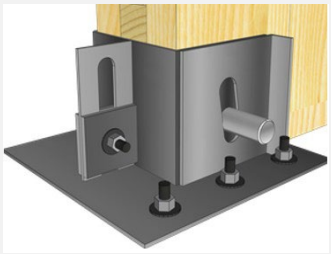
Connection name/Description	Connection figure	Materials	Reference
C13 - Panel to panel: T4 are a connection based on pairs of crossed fully threaded inclined screws stitching the panels.		CLT in 20 mm layers with a total thickness of 100 mm, elaborated on C24 class timber according to EN 338. 11 mm STS.	(Loss et al., 2016a)
C14 - Timber edge connection: Four typologies of adhesive free connections, each one allows to joint panels through interlocking doweled timber connectors to transfer bending moment loads.		Three layered CLT with defined standard wood MOE x: 8000 MPa y,z: 286 MPa Compressed wood Modulus of elasticity Ex: 32.85 MPa - Ey: 5.061 MPa Ez: 3.11 MPa Shear modulus. Gxy: 5.717 MPa - Gxz: 1.590 MPa Gyz: 878 MPa	(Ren et al., 2024b)
C15 - Shear connection: Connection with preloaded bolts inside a steel tube wall for enhanced slip resistance and contact surface.		Connection with preloaded bolts inside a steel tube wall for enhanced slip resistance and contact surface. Steel shear key grade S460. Steel beam IPE 400 S355 LVL with nominal thickness 144 mm. Partially threaded high-strength HV bolt, M20 × 210 mm, grade 10.9 Partial-thread timber screws, ⌀8 × 140 mm Würth ASSY 4 CSMP	(Romero and Odenbreit, 2024)
C16 - Moment connections: C16.1- Screwed spline Joins two adjacent CLT panels at their edges using plywood sheets attached with inclined STS		Seven ply CLT panel grade V2M6 Spline: 19.1 mm thick Baltic birch plywood, grade B Fasteners: Ø8 × 160 mm ASSY plus VG STS	(Hosseini et al., 2025)
C16.2 - Glued spline: Joins two adjacent CLT panels with plywood sheets bonded with adhesive. It creates a stiff, continuous connection to transfer bending moments		Seven ply CLT panel grade V2M6 Spline: 19.1 mm thick Baltic birch plywood, grade B. Adhesives: PL Premium Max and Titebond III.	(Hosseini et al., 2025)
C16.3 - T-joint: Joins two adjacent CLT panels with a T-shaped connector installed with STS		Seven ply CLT panel grade V2M6 Fasteners: Ø8 × 160 mm ASSY plus VG STS	(Hosseini et al., 2025)
Floor connections			
C16.4 - X-fix: Joins two adjacent CLT panels with an X-shaped dovetail acting as a shear key connector inserted into the CLT panels.		Seven ply CLT panel grade V2M6 Shear Key: Plywood grade B.	(Hosseini et al., 2025)

Table 2. Continued...

Connection name/Description	Connection figure	Materials	Reference
Wall to foundation connections			
C17 - X-rad: Corner connection fastened with screws to the CLT elements and through a bolted metal plate to other corner connections.		CLT made with softwood C24 class. Steel plates and metal connectors with hardwood inserts. Fasteners: M12 bolts and STS VGS ⌀11x350.	(Polastri et al., 2017)
C18 - X-mini: Corner anchor device design to resist both shear and tension loads.		three layered CLT with grade C24 timber. X-mini plates with fully threaded STS	(Casagrande et al., 2021)
C19 - Frictional based damper: Sliding metal plates pressed against each other by preloaded bolts.		FBD: Cold-bent S235 steel plates with preloaded M14 bolts Fasteners: Anker nails (⌀4–4 mm, length 60 mm), WHT340/WHT620 hold-downs. Shim Material: Aluminum	(Aloisio et al., 2022)
C20 - Modular base connection: Joints the self-centering CLT rocking wall to the foundation. Uses a shear pin to transfer lateral forces and a friction damper for energy dissipation.		Steel shoe of 6.35 mm A36 steel. Five ply CLT panel made with Spruce-Pine Fir No.2 Fasteners: Shear pin A50.8 mm Bolts ⌀19.1 mm SDS25600 Heavy-Duty Connector Screws	(Jerves and Phillips, 2024)

Notes: Timber and glulam strength classes (e.g., C24, GL24h, V2M6, E2), steel grades (e.g., S235-S460, A36) and proprietary fastener and hold-down designations (e.g., HBS, ASSY, VG, VGS, LBS, HV, SDS, WHT) follow the standard or manufacturer cited in the corresponding reference.

Surface-based fastening connections adapt conventional splines and stitchings and rely on fastener slip for stiffness. The Double-sided nail plate (C1) enhances shear capacity of perpendicular CLT panels through STS combined with a punched metal plate (Jacquier and Girhammar, 2014), functioning primarily as an InMC. Panel-to-panel spline systems for floor diaphragms include the crossed inclined-screw stitching (C13), the Screwed spline (C16.1) and T-joint (C16.3) (Hosseini et al., 2025), and the Glued spline (C16.2). Hybrid systems that integrate steel components target high structural demands: the Beam-to-panel connection (C12) uses welded plates with STS and epoxy resin, while the Shear connection (C15) is a demountable steel-tube/plate anchored to LVL with 60° STS and preloaded high-strength bolts, designed for off-site assembly with mortar-filled gaps for on-site activation, and explicitly compatible with disassembly and reuse.

Geometric interlocking connections rely on DfMA principles and CNC-milled interfaces (Li et al., 2024). Timber-only strategies include the Non-metallic double dovetail (C5, LVL) and Non-metallic dovetail (C8, cut directly in CLT) for perpendicular walls, with recommended tenon-to-panel thickness ratios (C5 < 2/3; C8 < 4/5) to avoid brittle failure; the Castellated joint (C9) and Double dovetail (C10, LVL) for wall-to-floor connections; the Timber edge connection (C14), machined into the second layer of adjacent CLT panels and secured by densified-wood (DW) dowels (Ren et al., 2024b; Mehra et al., 2021); and the X-fix shear key (C16.4), a plywood dovetail engaging and self-tightening the CLT without metal fasteners. Hybrid timber–steel interlocking designs include the Reversible connection (C2), with semi-spherical shear keys milled into the timber interface and steel bolts for confinement (Hansen et al., 2021); the Metal dovetail

connection (C3) for orthogonally adjacent panels without on-site fasteners; and the Slot connection (C4), a shear key inserted into milled grooves to enable monolithic wall behavior and to replace conventional spline fasteners (Polastri and Casagrande, 2022), well suited to InMC or IMC where high elastic stiffness is required.

Energy-dissipation connections implement the strong-fastener–weak-connector philosophy through replaceable metallic fuses or friction dampers. C6/C7 are 3D-printed male–female interlocking connectors (Binder Jetting, 60% 420 stainless steel + 40% bronze, 100 µm layers, 1 mm tolerance) that enable sliding assembly without on-site screwing or external access; the male part is engineered to yield plastically and protect the structural elements, with C6 restraining inter-modular drift and C7 resisting tension/uplift. The Ring connection (C11) is a steel-based system in machined grooves that supplies angle-bracket and hold-down functions and supports pre-installation for wall-to-floor and lateral configurations. The X-rad (C17) and X-mini (C18) are corner-mounted nodes anchored with double-inclined STS and joined via bolted steel plates, aimed at wall-to-foundation and wall-to-wall connection under seismic or wind-dominated conditions, and designed with DfMA, DfD and reuse in mind. Dedicated energy-dissipation devices include the Frictional base damper (C19), an asymmetric friction connection of five clamped steel plates between CLT walls and RC beams/slabs that activates at a preset slip force and behaves as a stiff link under moderate loads while dissipating energy during demanding events (Aloisio et al., 2022); and the Modular base connection (C20), a standardized self-centering base for rocking walls, with a steel shear pin and slotted hole for uplift, optionally augmented with an LSL wall-toe (Jerves and Phillips, 2024).

4.2 Mechanical performance and seismic suitability of connection technologies (RQ2)

The variability in objectives across the reviewed systems makes direct comparison challenging. Table 3 compiles peak strength, elastic stiffness (secant stiffness between zero and 40% of the maximum load, except for C8 and the C12 cyclic test, which consider the intersection between the origin and the maximum force value, as described in Loss et al. (2016b)) and ductility ratio µ (ratio of ultimate to yield displacement) for each system, together with the associated energy-dissipation mechanism. Because these values are drawn from heterogeneous protocols (EN 26891, ISO 6891, EN 12512, ISO 16670, EN 594, ACI ITG-5.1) with differing yield-displacement definitions and mix monotonic and cyclic results, they are treated here as indicative ranges rather than strictly comparable thresholds. The specimens were mostly C24 CLT (C1, C3, C4, C12, C13, C17, C18; Table 2), with Douglas fir (C9), hemlock (C5, C8), GL24h glulam (C10), V2M6 CLT (C16), LVL (C15) and SPF No.2 (C20). For reference, EN 338 (2016) assigns C24 timber characteristic strengths of 21 MPa in compression and 14.5 MPa in tension parallel to the grain and 4.0 MPa in shear, and EN 14080 (2013) assigns GL24h 24 MPa in bending and compression parallel to the grain. Because the connection capacities of Table 3 are governed by embedment, crushing or splitting of these base materials, whose properties scatter by species and grade, or by yielding of the steel components, they are compared as system values (kN, kN/mm, kNm) and not as material strengths.

Table 3. Engineering properties of modular CLT connections.

Name/ref	Energy dissipation	Type	Peak Strength				Stiffness				Ductility factor (µ)			
			Min	Max	Mean	Cov	Min	Max	Mean	Cov	Min	Max	Mean	Cov
			mechanism			(%)	(kN)			(%)	(kN/mm)			(%)
C1	Yielding and deformation of the metal fasteners combined with the crushing and deformation of the timber fibers around the connectors.	M1 s			16.1	5.3		19.4	7.3				2.7	
		M2 s			22.8	10.3		25.4	9.3				1.9	
		M3 s			44.1	6.2		72.2	12.4				10.2	
(Jacquier and Girhammar, 2014)		M4 s			51.5	7.2		85.0	10.4				11.0	
		M5 s			38.5	3.5		80.8	7.8				19.4	
		M6 s			33.9	4.9		45.6	21.0				15.7	
		M7 s			30.1	2.2		46.9	7.7				5.9	
		M8 s			32.9	3.2		53.6	7.8				19.5	
C2	Through ductile shear deformation and ductile failure of the shear keys and the connection bolt.	M1 s	3.0	8.5	4.8	29.8								
(Hansen et al., 2021)*														

Table 3. Continued...

Name/ref	Energy dissipation	Type	Peak Strength				Stiffness				Ductility factor (μ)			
			Min	Max	Mean	Cov	Min	Max	Mean	Cov	Min	Max	Mean	Cov
			mechanism			(%)	(kN)			(%)	(kN/mm)			(%)
C3 (Li et al., 2021)	Damage accumulation in the timber around the STS. including wood crushing and screw pull-out/fracture, leading to pronounced pinching behavior.	M1 t			75.1			13.3				1.7		
		M1 c			61.1			4.4				2.7		
		M1 s			45.0			3.4				2.9		
		C1 t			65.1	8.0		6.2	6.0			1.2		9.0
		C1 c			55.9	6.0		3.7	15.0			2.3		7.0
		C1 s			48.8	7		3.5	6.0			3.1		37
C4 (Polastri and Casagrande, 2022)*	Localized crushing of the wood or shear failure in the outer lamination of the CLT panels, with no plastic deformation of the connectors.	M1 s	94.0	180.0	132.8	26.4	8.3	32.6	18.9	42.7	2.0	5.0	3.1	33.7
C5 (Gao et al., 2023)*	Compressive deformation and cracking in the LVL tenons during rotation, combined with timber crushing of the CLT panels at mortise location.	M1 s	32.4	32.4	32.4		3.2	3.2	3.2		4.6	4.6	4.6	
		M2 s	31.2	31.2	31.2		2.8	2.8	2.8		2.3	2.3	2.3	
		M3 s	41.1	41.1	41.1		4.7	4.7	4.7		4.0	4.0	4.0	
		C1 s	30.6	34.5	32.2	5.5	2.2	3.6	2.8	21.1	1.9	4.3	3.1	35.6
		C2 s	27.2	28.2	27.6	1.6	1.7	2.5	2.0	19.8	1.7	2.6	2.3	17.8
		C3 s	38.3	47.3	42.3	9.7	2.4	2.9	2.6	8.4	1.9	2.5	2.2	14.5
C8 (Xu et al., 2024)*	Plastic deformation and crushing of the timber in the tenon neck and the adjacent area.	M1 s	33.1	33.1	33.1		6.2	6.2	6.2		3.0	3.0	3.0	
		M2 s	40.7	40.7	40.7		8.5	8.5	8.5		3.2	3.2	3.2	
		M3 s	51.0	51.0	51.0		8.9	8.9	8.9		11.4	11.4	11.4	
		C1 s	39.8	50.8	47.6	11.0	6.2	10.0	7.7	21.7	2.5	9.6	4.6	72.7
		C2 s	44.3	56.1	52.4	10.5	6.1	10.1	8.0	24.8	3.0	6.9	4.9	44.3
C9 (Brown et al., 2021)*	Crushing and compression deformation in castellated joint.	M1 s	66.0	170.0	120.0	26.2	14.0	80.0	50.5	44.1				
		M2 s	62.0	135.0	96.1	22.5	20.0	75.0	33.3	52.1				
C10 (Pomaroli and Kraler, 2023)	Ductile deformation of timber through the stepped tenon base that distributes load on multiple levels.	M1			26.0	11.0			8.1					
		M2			35.3	7.0			8.4					
C11 (Fanti et al., 2025)*	Plastic deformation of the steel tubular profile combined with the crushing and deformation of the timber fibers around the connectors.	M1 t	60.0	78.1	69.9	10.2	4.3	5.2	4.8	7.9	1.0	1.4	1.2	8.7
		M2 t	82.1	106.9	93.0	12.0	16.0	22.6	18.6	12.5	2.4	5.2	4.4	23.0
		M1 s	38.0	50.3	43.2	11.9	21.5	55.1	36.9	45.9	9.2	17.6	13.4	26.9
		M2 s	73.3	94.5	84.7	9.1	6.3	11.1	8.6	18.0	1.5	4.4	3.0	32.0
C12 C13 (Loss et al., 2016a)*	M1, M3, M4 configurations rely on yielding and shear-tensile failure of the metal fasteners. M2 relies on deformation and failure of the epoxy-based resin combined with timber deformation due to compression and shear.	M1 s	18.5	62.3	39.9	44.4	4.8	31.0	15.7	64.2	5.8	10.6	7.6	22.9
		M2 s	36.6	243.8	141.5	53.6	43.4	515	289.1	64.7	17.7	39.5	29.1	30.4
		M3 s	38.5	71.3	54.9	42.2	52.4	60.7	56.6	10.4	14.8	15.0	14.9	0.9

Table 3. Continued...

Name/ref	Energy dissipation	Type	Peak Strength				Stiffness				Ductility factor (μ)			
			Min	Max	Mean	Cov	Min	Max	Mean	Cov	Min	Max	Mean	Cov
			mechanism			(%)	(kN)			(%)	(kN/mm)			(%)
C17 (Polastri et al., 2017)	Plastic deformation of the steel components. Secondary, combined effects of localized failures inside the hardwood in tension configurations, and at the steel to CLT interactions due to compression forces.	C1 t	163.0	180.0	171.0	2.9				4.4	8.6	6.3		16.9
		C1 s	89.0	138.0	108.0	8.9				1.2	2.0	2.0		28.0
		C1 s-t	119.0	143.0	129.0	7.1				1.88	2.74	2.23		14.2
		C1 s-c	169.0	199.0	186.0	6.6				1.6	1.9	1.8		5.7
C18 (Casagrande et al., 2021)*	A combination of the plug shear failure of the inner layer of the CLT members and the withdrawal/deformation of the screws	M1 t	48.0	106.0	76.9	22.8	6.9	57.0	20.7	58.1				
		C1 s-t	65.5	105.6	86.0	16.3	7.0	17.9	14.4	25.1	1.9	3.6	2.7	22.6
		C2 s-t	30.8	66.5	48.7	31.5	1.1	2.6	2.0	39.6	2.3	3.1	2.6	18.1
C19 (Aloisio et al., 2022)*	Through controlled sliding and friction of the metal plates, clamped together by the preloaded bolts.	C1 s					11.5	354.3	150.3	83.4				
		C1 t					4.4	51.3	27.0	65.9				
			(kNm)				(kNm2)							
C14 (Ren et al., 2024b)	Compressive deformation and timber crushing in DW dowels (numerical results)	M1 b	0.4	4.2	1.9	67.0	1.0	15.3	6.3	75.0				
C15 (Romero and Odenbreit, 2024)*	Minor delamination of the LVL under maximum deformation of the beam.	M1 b	1,011	1,029	1,02	1.2								
C16.1 to C16.4 (Hosseini et al., 2025)	Plastic deformation of STS and frictional engagement in the zigzag joint configuration. Process	M1 b			33.3	4.0							2.3	21.0
		M2 b			35.5	9.0							1.0	0.0
		M3 b			17.1	7.0							3.2	20.0
		M4 b			8.1	7.0							2.2	15.0

Note: M: monotonic test, C: cyclic test, t: tensile test, s: shear test, c: compression test, b: bending test, st,sc: combined test. (*): Min, Max, Mean and CoV calculated through the available data of each source. C14: numerical results (Ren et al., 2024b).

4.2.1 Experimental methodologies

Monotonic loading of C1, C4, C9, C10, C11, C12, C13 and C15 followed EN 26891 (EN 26891, 1991), and of C16 ISO 6891 (ISO 6891, 1983). Cyclic testing for seismic behavior used EN 12512 (EN 12512, 2001) for C3, C6, C7, C12, C13, C17 and C18, and ISO 16670 (ISO 16670, 2003) for the non-metallic dovetails (C5, C8) and frictional dampers (C19). Full-scale validations used EN 594 (EN 594, 2011) for shear walls with the Slot connection (C4) and ACI ITG-5.1-07 (ACI ITG-5.1-07, 2007) for rocking walls with the Modular base connection (C20).

Table 4 lists, for each connection of Table 3, the reference, the test protocol, the definition of yield displacement used to derive the ductility ratio, the standard followed and the governing failure class. EN 26891 defines the monotonic procedure for joints made with mechanical fasteners (loading to 40% of the estimated maximum load, unloading to 10% and reloading to failure) and the slip modulus between 10% and 40% of the maximum load; it does not define a yield point. EN 12512 defines the reversed-cyclic procedure (three cycles per amplitude step, referred to the yield slip) and

the yield point as the intersection of the secant line between 10% and 40% of the maximum load with a tangent of one-sixth of its slope; strength impairment and equivalent viscous damping are derived from it. ISO 16670 defines a reversed-cyclic procedure with amplitude steps referred to the ultimate displacement of a monotonic test and does not prescribe a yield definition: C5 and C8 used the farthest-point method, and C19 the slip force of the friction interface. EN 594 defines the racking test of wall panels, and ACI ITG-5.1-07 the drift-controlled cyclic validation of rocking walls.

Because the ductility ratios in Table 3 depend on the yield definition of each source, they are compared only within the same definition and are otherwise read as indicative ranges. Most sources derived the yield displacement with the EN 12512 method, also for monotonic tests (C1, C3, C4, C11, C12, C13, C17, C18); C5 and C8 used the farthest-point method and C16 the ISO 6891 procedure. This is the case of C8, whose ductility factors of 11.4 and 14 reflect a low or ill-defined yield reference (Section 4.3.1). The last column of Table 4 groups the connections by the mechanism that governs failure - timber, fastener, connector or interface - which is the order used in Sections 4.2.2 and 4.2.3.

Table 4. Test protocols, yield-displacement definitions and governing failure class of the connections in Table 3.

Cxx/Reference	Test protocol	Yield-displacement definition	Standard	Governing failure class
C1 Jacquier and Girhammar (2014)	Monotonic shear, EN 26891 procedure (0.2 Fest/min); eight configurations	Yield slip by the EN 12512 method; ks between 10% and 40% of Fest	EN 26891; EN 12512	(ii) fastener: screw withdrawal with crushing of the timber around the fasteners
C2 Hansen et al. (2021)	Monotonic shear, displacement from the testing machine; no joint-test standard stated	Not reported (no ductility given)	None stated	(i) timber: shear of the timber keys; residual capacity in the bolts
C3 Li et al. (2021)	Displacement-controlled monotonic (3 mm/min; ultimate at failure, 80% Fmax or 30 mm) and cyclic (EN 12512 short procedure); withdrawal, push-down, shear	EN 12512 method	EN 12512	(ii) fastener: screw pull-out/fracture and wood crushing around the STS; pinching
C4 Polastri and Casagrande (2022)	Monotonic shear on panel-to-panel joints (EN 26891, 0.1 mm/s); monotonic racking of three-panel walls (EN 594, 0.2 mm/s)	EN 12512 method (10-40% secant and one-sixth tangent)	EN 26891; EN 594; EN 12512	(i) timber: localized crushing / shear of the outer lamination; connector elastic
C5 Gao et al. (2023)	Displacement-controlled monotonic (3 mm/min) and cyclic (amplitudes from the monotonic ultimate displacement); out-of-plane shear	Farthest-point method; ultimate at 80% Fmax; K between 10% and 40% Fmax	ISO 16670	(i) timber: cracking of the LVL tenon, crushing of the CLT at the mortise
C6/C7 Li and Tsavdaridis (2023a)	Quasi-static monotonic and cyclic on full-scale shear (C6) and tensile (C7) units	Not reported (no ductility given)	EN 12512	(iii) connector: bending of the male steel connector, screws intact
C8 Xu et al. (2024)	Displacement-controlled monotonic (3 mm/min) and cyclic (0.25 mm/s, modified amplitudes); out-of-plane shear	Farthest-point method; ultimate at 80% Fmax; K between 10% and 40% Fmax	ISO 16670	(i) timber: crushing at the tenon neck, splitting, fracture of the middle panel
C9 Brown et al. (2021)	Monotonic shear, EN 26891 procedure (2-4 mm/min); ultimate at 80% Fmax per EN 12512	Not reported	EN 26891; EN 12512	(i) timber: crushing in the castellation; longitudinal shear of the tenon, rolling shear
C10 Pomaroli and Kraler (2023)	Monotonic, EN 26891, on beam combinations and on 3-point bending of CLT elements	Not reported	EN 26891	(i) timber: ductile deformation of the stepped tenon base
C11 Fanti et al. (2025)	Monotonic tension and shear, EN 26891 procedure; three tests per configuration	Trilinear-curve yield point per EN 12512; stiffness from Fmax or F15 per EN 26891	EN 26891; EN 12512	(iii) connector: plastic deformation of the steel tubular profile with crushing of the timber around it

Table 4. Continued...

Cxx/Reference	Test protocol	Yield-displacement definition	Standard	Governing failure class
C12/C13 Loss et al. (2016a)	Monotonic (EN 26891, 0.05 mm/s) and cyclic (EN 12512) push-pull in two shear planes	EN 12512 method, with a slip limit of 15 mm instead of 30 mm	EN 26891; EN 12512	(ii) fastener: yielding and shear-tensile failure of the STS (M1, M3, M4); adhesive and timber (M2)
C14 Ren et al. (2024b)	Numerical: four-point bending finite element models (ABAQUS) validated against the tests of Mehra et al. (2021) and Sotayo et al. (2020); no physical test of the connection	Not applicable	None	(i) timber: crushing of the DW dowels; delamination and rolling shear at the connector edges
C15 Romero and Odenbreit (2024)	Monotonic six-point bending of two full-scale STC beams; load-unload cycle per EN 26891 and Eurocode 4 Annex B	Not reported	EN 26891 (procedure)	(iii) connector (steel-timber composite): minor delamination of the LVL at maximum deformation
C16.1-C16.4 Hosseini et al. (2025)	Monotonic four-point bending, modified ISO 6891 (8 mm/min; 40%-10% cycle; failure at 80% Fmax)	dY per ISO 6891; du at 80% of the peak load	ISO 6891	(ii) fastener: plastic deformation of the STS (C16.1, C16.3); (i) adhesive/timber (C16.2); (i) plywood shear key (C16.4)
C17 Polastri et al. (2017)	Cyclic (EN 12512) in tension and shear; monotonic (0.1 mm/s) in shear-tension and shear-compression	EN 12512 (Fy, vy)	EN 12512	(iii) connector: plastic deformation of the steel components; secondary local failure of the hardwood inserts
C18 Casagrande et al. (2021)	Monotonic (K between 10% and 40% Fmax) and cyclic (EN 12512) at 0, 90, +45 and -45 degrees	EN 12512 method	EN 12512	(iii) connector: plug shear of the inner CLT layer with screw withdrawal/deformation
C19 Aloisio et al. (2022)	Cyclic, adapted from ISO 16670 (amplitudes as fractions of the ultimate displacement)	Slip force of the friction interface	ISO 16670	(iv) interface: controlled sliding of the clamped steel plates
C20 Jerves and Phillips (2024)	Cyclic rocking-wall test, three reversed cycles per drift level from 0.035% to 4.0% (38.1 mm/min)	Not reported	ACI ITG-5.1-07	(iv) interface: rocking with shear pin and damper; STS withdrawal at the wall toe only in unreinforced specimens

Note: (i) timber-governed, (ii) fastener-governed, (iii) connector-governed, (iv) interface-governed; the classes are ordered by increasing damage avoidance (Section 4.2.3). Configurations (M/C, t/s/c/b) as in Table 3.

4.2.2 Surface-based vs. geometric interlocking connections

Geometric interlocking systems that directly engage the timber in compression and shear consistently deliver superior capacity and stiffness. The Slot connection (C4) reached a mean peak strength of 132.8 kN and elastic stiffness of 18.9 kN/mm, and the Castellated joint (C9) reached 120 kN and 50.5 kN/mm — approximately seven times the stiffness of comparable commercial angle brackets (Titan TTN240). This performance carries stress-concentration risk: C4 exhibited limited ductility in full-scale wall tests ($\mu \approx 3.1$), with near-elastic response governed by timber splitting rather than connector yielding. In C9, primary failure modes (longitudinal shear of the tenon and rolling shear of the CLT layers) generated a reinforcing effect that prevented sudden load drops after failure.

Surface-based systems modifying the panel contact plane exhibited lower initial stiffness due to fastener slip. The Double-sided nail plate (C1), tested across eight configurations (M1–M8), reached a mean peak shear strength of up to 51.5 kN (M4), but its reliance on a perpendicular screw for confinement leads to significant slip after direct extraction. The Reversible connection (C2) showed substantial capacity gains relative to a control without shear keys (approximately three-fold in some cases, inferred from graphical data in Hansen et al. (2021)), with primary failure by shear of the timber keys and residual capacity provided by the steel bolts. Used as InMC, the compliance of surface-based systems can delay the activation of the global lateral-resisting system.

The mechanism that governs failure separates the reviewed systems into the four classes of Table 4. In the timber-governed class the capacity is set by crushing, splitting or rolling shear of the CLT: C4 and C9 deliver high stiffness but fail through localized crushing of the wood with no plastic deformation of the aluminum connector (C4) or through longitudinal shear of the tenon and rolling shear of the layers (C9), and the timber-only dovetails C5, C8 and C10 fail

through crushing or splitting of the tenon and the mortise, which is why ductility degrades under cyclic loading in C5 (μ from 4.0 to 2.2; Section 4.3.1). In the fastener-governed class the failure sits in the screw or nail group: screw withdrawal in C1, screw pull-out and tensile splitting at the fastener groups in C3, so that the steel dovetail of C3 remains undamaged while reusability is lost through the fasteners (Section 4.3.2); in C12/C13 and in the screwed splines C16.1 and C16.3 the STS yield in a ductile way.

In the connector-governed class the steel component acts as the fuse: bending of the male connector in C6/C7 with the screws intact, followed in the later cycles by stiffness degradation due to elastic deformation of the walls of the female connector (Li and Tsavdaridis, 2023a); plastic deformation of the tubular profile in C11 and of the steel plates in C17; C18 combined the plug shear failure of the inner CLT layer with withdrawal and deformation of the screws (Casagrande et al., 2021). In the interface-governed class (C19, C20) damage is limited to controlled sliding or rocking; in C20 the only timber damage observed was the withdrawal of the STS attaching the steel shoe to the wall toe of the unreinforced specimens under high clamping forces, which the LSL wall toe removed (Jerves and Phillips, 2024). The order of the four classes is the order of increasing damage avoidance and reusability developed in Section 4.2.3.

4.2.3 Damage avoidance hierarchy and seismic energy dissipation

For seismic demand, the reviewed connections span a hierarchy of damage-avoidance strategies. At the least favorable end, systems such as the Double-sided nail plate (C1) dissipate energy through destructive screw withdrawal (gaps of 10–20 mm between connected members), and the Double dovetail (C10) delays brittle failure until roughly 10 mm of deformation through a stepped tenon geometry, but relies on wood damage that limits disassembly and reuse relative to systems with replaceable metallic fuses.

High-ductility yielding-metallic connections protect the timber panel through controlled steel yielding. The X-Rad (C17) achieved μ = 6.3 with a mean peak tension strength of 171 kN; the X-mini (C18) reached 106 kN with 20.7 kN/mm stiffness for lighter loads; the Ring connection (C11) reached ductility ratios up to 17.6 in specific configurations. The Shear connection (C15) reached an elastic limit around 600 kNm (60 mm mid-span deflection) and a maximum bending moment of 1,029 kNm — orders of magnitude higher than timber-only solutions like C14 and C16.2 and C16.4, positioning C15 as the only reviewed option for long-span modular flooring provided steel profiles are integrated; slip values below 1 mm at service loads indicate that panels can be reused under service conditions. Systems specifically designed for energy dissipation sit at the top of the hierarchy and typically function as MFC. The Frictional base damper (C19) achieves a stable 50% drift reduction through controlled sliding with aluminum plates and 36 kN preloaded bolts, with an optimal slip force of approximately 23% of the frame shear resistance (~45 kN). The Modular base connection (C20) exhibited an elastic stiffness of 5.7 kN/mm, post-decompression stiffness of 1.4–1.5 kN/mm, negligible residual drift (0.2%) and no visible crushing at the wall toes when reinforced — supporting immediate post-event occupancy. In C6/C7, plastic deformation was successfully confined to the bending of the male steel connector, with screws remaining intact, confirming the ability to localize plastic deformation within the replaceable steel element; the tensile configuration reached 29 kN with superior ductility to the shear configuration (Li and Tsavdaridis, 2023a).

Palmiotta et al. (2023) further show that controlled shear-slip mechanisms — closely analogous to those of C19 and C20 — govern the seismic response of modular structures, supporting the extension of these families to IMC and MFC roles pending refinement and validation in CLT modular construction.

Taken together, the connections best suited to demanding seismic applications are those that (i) decouple energy dissipation from the timber element, (ii) place damage in replaceable metallic or frictional components, and (iii) retain stiffness and strength through repeated cycles. Timber-only interlocking joints, on their own, are generally unsuitable as the primary seismic-dissipative element in high-demand regions, because their energy dissipation relies on irreversible and non-repeatable timber damage (crushing and splitting); this reflects the current detailing of these joints rather than a fundamental limit on timber-only dissipation.

On the compiled values, the selection by structural role is as follows. Where high elastic stiffness is required in InMC or IMC, the Slot connection (C4, 132.8 kN, 18.9 kN/mm) and the Castellated joint (C9, 120 kN, 50.5 kN/mm), accepting timber-governed failure and low ductility (μ about 3). For IMC and MFC under seismic demand, the yielding-metallic systems X-Rad (C17, μ = 6.3 at 171 kN) and Ring (C11, μ up to 17.6), which place damage in a replaceable steel component, and the X-mini (C18, 106 kN, 20.7 kN/mm) for lighter loads. Where post-event reusability governs, the Frictional base damper (C19) and the Modular base connection (C20, residual drift 0.2%). For long-span modular floors, the Shear connection (C15, 1,029 kNm, slip below 1 mm at service loads). Timber-only interlocking connections (C5, C8, C10, C14) are recommended for InMC under low to moderate seismic demand only, because their ductility relies on irreversible timber damage.

4.3 Trade-offs between circularity, seismic resilience and reusability (RQ3)

4.3.1 The timber-only vs. reusability trade-off

Timber-only interlocking joints align with circularity goals but consistently struggle with reusability. The Non-metallic double dovetail (C5), in its third configuration (0.75 tenon-width-to-panel-thickness ratio), reached a maximum peak strength of 41.1 kN (monotonic) and 47.3 kN (cyclic), with elastic stiffness of 4.7 kN/mm and $\mu = 4$ monotonically, but cyclic loading dropped stiffness to 2.6 kN/mm and ductility to 2.2. Its failure modes — damage transferring from tenon to CLT panels, severe splitting and wood crushing within the mortise and side panels — directly hinder reusability. The Non-metallic dovetail (C8) reached high ductility factors (11.4 and 14 for the M3 and C3 configurations) that reflect a low or ill-defined yield reference rather than reliable, degradation-inclusive cyclic seismic ductility with a mean peak strength of 52.2 kN and stiffness of 6.6 kN/mm, but through timber crushing near the tenon neck, splitting and fracture of the middle CLT panel, again intensified by combined shear and induced bending. The same trade-off appears in bending-tested connections: the Glued spline (C16.2) reached 35.5 kNm but failed abruptly with $\mu = 1.0$, and the T-joint (C16.3) and X-fix (C16.4), operating as pure shear keys, reach lower capacity. The Timber edge connection (C14) prioritizes circularity at the cost of capacity (mean flexural capacity of only 1.9 kNm, max 4.2 kNm), restricting its use to short spans, though failure is ductile through delamination and rolling shear at the connector edges (104.6 mm displacement at failure).

4.3.2 Hybrid strategies as an integrating pathway

Hybrid connections shift damage away from the timber and enable reusability under higher demand. The Metal dovetail (C3) exhibited its highest capacity under monotonic withdrawal (75.1 kN, 13.3 kN/mm) but with a low $\mu = 1.7$, with failure concentrated in fastener groups (screw pull-out and tensile splitting in withdrawal) rather than the steel dovetails; despite this, it reached overstrength factors of 1.54 in shear and 1.86 in compression, and behaves as a semi-rigid link with reserve capacity that supports capacity-based seismic design provided fastener arrangements are optimized to prevent brittle withdrawal (Li et al., 2021). The C6/C7 interlocking systems concentrate plastic deformation on the bending of the male steel connector, leaving the screws intact — an outcome that directly enables reusability of the structural components of the module. At the top of the damage-avoidance hierarchy, dedicated energy-dissipation devices (C19, C20) preserve the module geometry, since energy is dissipated in sliding steel plates (C19) or in the rocking mechanism with steel shear pin and slotted hole (C20). Only these decoupled systems achieve true reusability in high-seismic zones. Consequently, for modular CLT to be viable in earthquake-prone regions, design must consider the whole load path — InMC, IMC and MFC — rather than optimizing individual connections in isolation.

4.3.3 Fabrication, materials and circularity innovations

Digital fabrication is accelerating connector innovation. CNC milling and 3D printing enable high-precision joints with reduced labor and assembly error (Tenório et al., 2024), though precision alone does not guarantee assemblability: Rogeau et al. (2022) show that a 5-degree taper combined with 5 mm chamfers is required to reconcile the tight tolerances needed for structural rigidity with the force limitations of industrial robotic arms, and this geometric optimization enables simultaneous insertion of multiple through-tenon joints — a critical requirement for volumetric InMC assembly.

Material compatibility is emerging as a defining feature. In the Slot connection (C4), aluminum connectors showed no residual plastic deformation while the timber suffered localized crushing (Polastri and Casagrande, 2022), highlighting that mismatches in stiffness prevent full utilization of components. DW dowels offer corrosion resistance, compatibility with timber's hygrothermal behavior, and reduced maintenance demand (Hansen et al., 2021; Loss et al., 2016a), with compressive strengths up to 164 MPa (Sotayo et al., 2020) — far exceeding conventional structural timber (C24, 21 MPa (EN 338, 2016)) and viable for high-demand connections (Ren et al., 2024b). Future hybrid designs must therefore balance the yield points of metallic and timber components.

Circularity is also driving innovation at the system level. Foldable CLT arches with rotational press-fit (RPF) joints (Al-Qaryouti et al., 2019; Alqaryouti et al., 2021) demonstrate predictable strength governed by flexural resistance, and the BUGA Wood Pavilion (Bechert et al., 2021) shows how prefabricated CLT segments joined by bolted and finger joints can form lightweight, column-free shells, while also highlighting the importance of joint stability and positional control during reassembly. Timber–cork modular systems (Barreca et al., 2022) resisted hurricane-level wind speeds up to 72 m/s (F3), while reconfigurable modular timber grids (Hua et al., 2022) enable elements to be reused across multiple projects. Enhanced seismic capability comes from combining frictional-based components with self-centering capabilities: clamped-steel-plate frictional damping (Jerves and Phillips, 2024) shows high energy dissipation but less predictable unloading behavior, while hybrid steel–timber connectors (Li and Tsavdaridis, 2023a; Romero and Odenbreit, 2024)

concentrate damage in ductile replaceable elements. Replaceable elements can extend the structural lifecycle, but only if the structural system is demountable or provides access for the replacement parts.

4.4 Knowledge gaps and research priorities for standardization and wider adoption (RQ4)

4.4.1 Scarcity of full-scale validation and modeling challenges

A recurring limitation across recent developments in connection design is the scarcity of full-scale experimental validation for modular CLT structures. While numerous studies provide valuable insights through connection-level monotonic and cyclic tests (Polastri and Casagrande, 2022; Brown et al., 2021; Li et al., 2021; Li and Tsavdaridis, 2023a; Jerves and Phillips, 2024; Hosseini et al., 2025; Fanti et al., 2025; Polastri et al., 2017), complementary studies are required to reveal the complex demands and interactions generated by seismic loading at the full-scale modular level. Seismic performance validation therefore relies heavily on Finite Element Models (FEM), which must reproduce controlled ductility, reliable energy dissipation and resilience under realistic boundary conditions. Translating experimental behavior into design models remains complex: even within well-established typologies such as light-frame timber, empirical connection data reveal discrepancies with isolated component-level studies (Catalán et al., 2026; Valdivieso et al., 2025). For instance, in Double-sided nail plates (C1) total capacity is not the simple superposition of components, as the plate and screws peak at different slip values. Component-based elastic-spring models have been successfully derived for Castellated joints (C9), but energy-dissipation devices such as Frictional Dampers (C19) present modeling challenges — particularly regarding velocity-dependent behavior during hysteresis — with direct implications for reliable seismic analysis.

Robust FEM depends on valid conceptual frameworks, and experimental campaigns are essential for characterizing energy dissipation and specific failure mechanisms (brittle fractures, shear-key slippage, compressive buckling) (Polastri and Casagrande, 2022; Li and Tsavdaridis, 2023a; Aloisio et al., 2022; Palmiotta et al., 2023; Casagrande et al., 2021). Bhandari et al. (2023b) leveraged the "three-link element" approach derived from X-rad and X-mini studies to simulate point-type connections as multi-linear links (vertical, horizontal, diagonal) in OpenSees, showing that screwed coupled walls in InMC systems can achieve near-monolithic ratios of ductility and equivalent viscous damping, and that fastener spacing above 180 mm prevents concentrated panel damage while spacing below 150 mm limits inter-storey drift at the cost of ductility.

4.4.2 Cost, tolerance and three-dimensional effects

Even in validated systems such as X-Rad and X-Mini (Polastri et al., 2017; Casagrande et al., 2021), development is hindered by high initial equipment costs, oversized and complex designs, and the sheer variety of non-standardized designs (Li and Tsavdaridis, 2023a; Loss et al., 2016a; Polastri et al., 2017; Hua et al., 2022). Conventional manufacturing tools (welding, laser cutting, handheld power tools), expensive 3D-printing techniques and complex geometry each contribute to these costs; broader adoption of 3D printing and large-scale implementation are expected to reduce them (Li and Tsavdaridis, 2023a). Capitalizing on simplified connection systems through streamlined design, verification, assembly, disassembly and installation is therefore essential (Polastri and Casagrande, 2022). Beyond cost, three-dimensional effects and tolerances persist as challenges (Ahmed et al., 2025; Pei et al., 2024): vertical joints and box-like effects remain underexplored despite their potential to alter global stiffness (Polastri et al., 2017); swelling or shrinkage of CLT panels during transport can complicate on-site installation of interlocking metal connections (Li et al., 2021); and specific geometric features such as bevels and chamfers can effectively compensate for minor material deviations and positioning errors during robotic assembly (Rogeau et al., 2022).

4.4.3 System-configuration effects

Connection performance cannot be evaluated in isolation, since it is shaped by system configuration — specifically the location of InMC and IMC and the distribution of modules. Miedziałowski et al. (2023) found that InMC exert a much greater influence on overall stiffness than IMC, while variations in opening size can reduce wall resistance by up to 34%. These effects show that architectural design choices directly affect structural reliability by altering load distribution and creating stiffness imbalances, potentially forcing InMC to resist complex torsional forces beyond their intended role.

4.4.4 Normative bias and geographic transferability

The bibliometric analysis (Section 4.1.1) confirms that connection development and testing are largely aligned with local standards, particularly Eurocode 8 (2004). Reported performance data on inter-storey drift limits, ductility factors and stiffness degradation are therefore optimized for the moderate seismicity typical of European regions rather than for the extreme demands of subduction zones. Direct transferability of these technologies to countries such as Chile,

Japan or Peru — governed by NCh 433 (2009), NTE E.030 (2016) and the Building Standard Law (1950) respectively — is limited, and future research must rigorously test modular systems against a broader range of seismic and regulatory frameworks.

4.4.5 Research priorities

To bridge the gap between research prototypes and scalable solutions, the review identifies three research priorities:

- Full-scale validation of locally tested connections, moving beyond connector tests to validate "box-like" behavior and vertical-continuity effects.
- Development of design guidelines that explicitly link stiffness compatibility between InMC and IMC to prevent torsional imbalances.
- Durability modeling and testing to quantify long-term degradation mechanisms — covering corrosion, preload relaxation from perpendicular-to-grain timber creep, and fastener fatigue, with hydrogen embrittlement relevant only to high-strength preloaded bolts — to ensure that "design for reuse" is viable over multiple lifecycles.

Together, these priorities frame the standardization and industrial-adoption agenda for modular CLT connections in seismically active regions.

5 DISCUSSION

The RQ-organized results consolidate three integrating findings that cut across the connection literature.

First, the functional taxonomy of InMC / IMC / MFC (RQ1) provides an organizing frame that is absent from the component-focused view of prior reviews (Heidari et al., 2025; Zambrano-Jaramillo and Fischer, 2026). Because IMC placement and detailing govern diaphragm behavior and can alter shear and moment demands on gravity columns by more than 60% (Lacey et al., 2018), performance evaluation must be conducted at the system level rather than at the isolated joint. Despite growing evidence of the structural and sustainability benefits of modular construction, its widespread adoption still faces resistance for both economic and cultural reasons (Thirunavukkarasu et al., 2021); hybrid systems offer a pragmatic pathway, and early Beam-to-panel (C12) and crossed-screw stitching (C13) developments established the foundational potential for composite action, with newer systems such as those of Romero and Odenbreit (2024) refining these concepts for demountability.

Second, the mechanical performance evidence (RQ2) shows that the "strong fastener–weak connector" philosophy is the design invariant behind every solution that combines high ductility, stable hysteresis and low residual damage — from yielding-metal systems (C6/C7, C11, C17/C18) to dedicated dissipative devices (C19, C20). Timber-only interlocking joints, by contrast, are, as currently detailed, generally unsuitable as the primary seismic-dissipative element on their own, because their energy dissipation relies on irreversible and non-repeatable timber damage.

Third, this incompatibility is the core of the circularity trade-off (RQ3). True reusability in high-seismic zones is achieved only by decoupling energy dissipation from the timber element through hybrid or dissipative systems that preserve module geometry. Circularity innovations — DW dowels (Ren et al., 2024b; Mehra et al., 2021; Hansen et al., 2021; Loss et al., 2016a), robotic assembly with tolerance-absorbing geometric features (Rogeau et al., 2022), reconfigurable timber grids (Hua et al., 2022) — are therefore most productive when embedded in a system-level design that also satisfies seismic requirements.

Design strategies emphasizing adaptability and rapid deployment further extend the scope of modular CLT. Foldable and deployable designs (Al-Qaryouti et al., 2019; Alqaryouti et al., 2021) facilitate transport, assembly and reuse for emergency and temporary structures; repetitive modular patterns standardize connection types, accelerating construction and reducing costs. The knowledge gaps identified under RQ4 — full-scale validation, cost and tolerance issues, three-dimensional effects, system-configuration sensitivities and normative bias — sit above these three findings as the conditions that need to be resolved before the field can move from prototype to standardized industrial practice.

6 CONCLUSIONS

This systematic review consolidates the current state of knowledge on connection systems for modular CLT structures, establishing a functional taxonomy — InMC, IMC and MFC — and analyzing 50 studies through a PRISMA-based protocol and a bibliometric assessment. The four research questions guiding the review can be answered with the available evidence:

RQ1. The field is active but geographically and thematically concentrated (163 authors, 27 countries, dominated by Italy, the UK, China and the US), organized around three thematic clusters (modular construction/circularity; structural/seismic; numerical modeling), and connection systems can be functionally classified into InMC, IMC and MFC that together define the load path in modular CLT structures.

RQ2. The comparative performance analysis reveals a critical design interchange between constructability and seismic resilience: timber interlocking connections (e.g. dovetails) align with DfMA and circular-economy goals but currently exhibit ductility that derives from irreversible timber crushing and splitting and that degrades under repeated cycles; hybrid steel–timber systems and frictional dampers consistently concentrate inelastic demand in replaceable metallic or frictional components and therefore deliver the higher, stable and repeatable hysteresis required for demanding seismic zones. Advancing modular construction in earthquake-prone regions therefore requires a shift toward "strong fastener–weak connector" philosophies in which damage is concentrated in replaceable metallic fuses.

RQ3. The primary trade-off is between eliminating adhesives and steel (favoring circularity) and preserving module geometry under cyclic seismic demand (favoring reusability). Circularity is achievable through innovations such as the C15 shear connection, which maintains elastic behavior with slips under 1 mm at service limits, but true reusability in high-seismic zones requires hybrid or dissipative systems that decouple energy dissipation from the timber element.

RQ4. The main knowledge gaps concern industrial uptake (cultural resistance, economic barriers, supply-chain constraints) and technical consolidation (standardized testing, validated numerical/analytical models, integrated design frameworks that explicitly address durability, circularity and system-level performance). Future research must prioritize: (i) full-scale validation moving beyond connector tests to "box-like" behavior and vertical-continuity effects; (ii) design guidelines that explicitly link stiffness compatibility between InMC and IMC to prevent torsional imbalances; and (iii) durability modeling and testing that quantify long-term degradation mechanisms so that "design for reuse" is viable over multiple lifecycles. Addressing these challenges will enhance the seismic resilience and efficiency of modular CLT systems and solidify their role as scalable, sustainable solutions for the built environment.

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APPENDIX A

A.1 Scope of the closest prior reviews

Table A1 compares the scope of the three closest prior reviews with that of the present review, criterion by criterion.

Table A1. Scope of the three closest prior reviews compared with the present review.

Criterion	Bhandari et al. (2023a)	Heidari et al. (2025)	Zambrano-Jaramillo and Fischer (2026)	This review
Object of review	Built modular CLT projects: design, manufacturing, logistics	CLT shear-wall connections: mechanical database	Inter-modular connections of volumetric CLT	Connections of volumetric CLT along the load path
Scope in the load path	Intra-, inter-modular and module-to-foundation named; described from projects, no mechanical data	Connection and assembly level (wall-to-floor, wall-to-wall) for panelized shear walls	Inter-module interface only; intra-module mentioned in passing	InMC, IMC and MFC as one load path, with mechanical data for each
Construction system	Volumetric (3D) and flat-pack (2D) modular CLT	Panelized (platform-type) CLT	Volumetric CLT modules	Volumetric CLT modules
Evidence base	72 projects, 122 buildings (2005-2021); demonstration projects	522 connection sets, 2,048 test specimens	7 inter-modular systems; inventory of built projects	50 publications; 20 connection systems (C1 to C20)
Selection protocol	Keyword search plus grey literature, LinkedIn, snowballing; no reported flow	Literature compilation, peer-reviewed only; protocol not reported	Keyword search plus industry sources; protocol not reported	PRISMA 2020 with reported flow and snowballing; grey literature excluded
Mechanical data	None (project descriptions)	Quantitative (slip modulus, yield and maximum strength, ductility)	Qualitative multi-criteria scoring; quantitative comparison explicitly not attempted	Quantitative ranges (peak strength, stiffness, ductility; monotonic and cyclic)
Circularity and reuse	Reusability of temporary modules discussed qualitatively	Not addressed	Design for disassembly scored qualitatively (0 to 2)	Quantitative cyclic data set against reusability; damage-avoidance hierarchy
Hazard scope	Seismic hazard of project sites mapped	Seismic (connection level)	Seismic and wind, with hazard mapping of built projects	Seismic only
Code and geographic bias	Geography of projects mapped; code bias not addressed	Not addressed	Geography of projects mapped; code bias not addressed	Addressed (Eurocode 8 alignment vs NCh 433, NTE E.030, Building Standard Law)

Note: Two of the seven systems scored by Zambrano-Jaramillo and Fischer (2026) are in the present corpus (their IMC-2 corresponds to C6/C7 and their IMC-3 to C17). Ren et al. (2024a) and Ottenhaus et al. (2023) are not tabulated because neither addresses modular construction.

A.2 Summary of the reviewed studies

A summarized overview of the studies considered in this review can be found in Table A2; the numbers in the Reference column refer to the list at the end of this appendix.

Table A2. Summary of the reviewed studies.

Title	Type of connection	Methods	Reference
Structural performance of CLT shear connections with castellations and angle brackets	Castellated joint Steel brackets	Monotonic and cyclic test Comparative analysis Analytical modelation	[1]
Design of a novel seismic retrofitting system for RC structures based on asymmetric friction connections and CLT panels	Frictional dampers	Hysteresis model Experimental cyclic test	[2]
Computational design and digital fabrication of folded timber sandwich structures	Interlocking rotational press fit joint Shear key hinge	Computation model and design Monotonic test Accuracy analysis	[3]
Structural behavior of folded timber sandwich structures	Rotational press fit joint	Computation model and design Simplified 2D modeling	[4]
Experimental evaluation of a modular timber unit filled with insulated corkboard	Finger joints	Glued connection Module connection under vertical load Characterization of cryptomeria wood	[5]
Potential of Sustainable Timber Modular Houses in Southern Highland, Tanzania: The Structural Response of Timber Modules Under Wind Load	Steel nails Steel brackets	Python scripts Abaqus 3D model	[6]
A Highly Sustainable Timber-Cork Modular System for Lightweight Temporary Housing	Steel brackets	Finite element model Thermal analysis Sustainability analysis	[7]
Integrative structural design and engineering methods for segmented timber shells - BUGA Wood Pavilion	Bolted connection Finger joint Screw connection	Computational design of shells Finite element model	[8]
Numerical assessment of In-plane behavior of multi-panel CLT shear walls for modular structures	Point type inter and intra modular connections	Monotonic and cyclic testing Lateral loading Opensees simulation comparison	[9]
Structural performance of a hybrid timber wall system for emergency housing facilities	X-Mini	Monotonic and cyclic testing Full scale wall modules testing finite element model in SAP2000	[10]
Structural performance of CLT moment connections in the minor strength axis	Screwed splines Glued splines Screwed T-joints Wooden X-fix shear key	ISO 6891 loading protocol Bending tests Numerical modeling	[11]
Reconfigurable Modular System of Prefabricated Timber Grids	Shallow nothed joints	Finite element modeling Robotic milling system	[12]
Tests on glulam–CLT shear connections with double-sided punched metal plate fasteners and inclined screws	Shear connection system	Loading procedure EN 26891 Shear tests Model comparison for stiffness and capacity	[13]
The role of intermodular connections in the global behavior of the high-rise mass timber buildings	Node elements in Opensees model	Parametric analysis of Opensees models Key parameters of connections	[14]
Cyclic testing and modeling of CLT rocking walls with modular base connections and LSL wall toes	Shear pin with friction damper	Cyclic testing Non linear modeling Comparisson analysis	[15]

Table A2. Continued...

Title	Type of connection	Methods	Reference
Harmonization of Structural and Functional Lifespans of Prefabricated Residential Buildings	Detachable connections	Conceptual proposal of modular building	[16]
Mechanical performance and contact zone of timber joint with oblique faces	Scarf Joints Dowell	Digital Image Correlation Bending test EN408	[17]
A novel interlocking dovetail connection system for cross laminated timber volumetric structures	Interlocking connection system	Monotonic and cyclic test Numerical analyses	[18]
Design for Seismic Resilient Cross Laminated Timber (CLT) Structures: A Review of Research, Novel Connections, Challenges and Opportunities		Bibliographic review	[19]
Limited-damage 3D-printed interlocking connection for timber volumetric structures: Experimental validation and computational modelling	Interlocking connection	Monotonic and cyclic test Numerical analyses	[20]
A novel limited damage 3d-printed interlockin inter-module connection system for cross laminated timber volumetric structures	Interlocking connection system	Monotonic and cyclic test Numerical analyses	[21]
Reusable timber modular buildings, material circularity and automation: The role of inter-locking connections	Interlocking connection system	Connection system review Case study	[22]
Connections for steel–timber hybrid prefabricated buildings. Part I: Experimental tests	screwed connection Steel beam to panel Steel beam to panel edge	Push out test Double shear plane Monotonic load under EN 26891	[23]
Connections for steel–timber hybrid prefabricated buildings. Part II: Innovative modular structures	screwed connection Steel beam to panel Steel beam to panel edge	Finite element modeling	[24]
Experimental investigation on in-plane stiffness and strength of innovative steel-timber hybrid floor diaphragms	Bolts and screws Steel beam to panel	Monotonic and cyclic test Full scale floor test	[25]
Innovative composite steel-timber floors with prefabricated modular components	Bolts and screws Beam to panel	Monotonic and cyclic test Full scale floor bending test	[26]
A numerical study of prefabricated full-scale light-frame timber modules	Elastomeric bricks	3D Finite element model	[27]
including inter-modular connections		Full size module test	
Stiffness of Experimentally Tested Horizontally Loaded Walls and Timber-Framed Modular Building	Dowel fasteners	Wall panel testing EN 594	[28]
Seismic behaviour of steel modular buildings: numerical analysis and comparisons between different design solutions	Interlocking bolted inter-module connection	Numerical modelation coparison	[29]
Challenges in the design of modular multi-store CLT building using irish timber		Design summary	[30]
Load-bearing furniture modules	Bolted connections	Design criteria definition	[31]
for fast deployable and reusable		Reversible connection proposal	
systems			
Innovative demountable steel-timber composite (STC) beams: Experimental	shear connection	Bending test	[32]
full-scale bending tests	steel tubes	Escalonated load EN 26891	
Contemporary Strategies for the Structural Design of Multi-Story Modular Timber Buildings: A Comprehensive Review		Literature review	[33]
Sustainable Performance of a Modular Building System Made of Built-Up Cold-Formed Steel Beams		Literature review	[34]
Prototyping Architecture: A flat-pack timber plate structure from design to production	Cleat Joint	Design proposal and prototype of pavilion	[35]
Out-of-plane shear performance of a novel non-metallic CLT dovetail joint	Dovetail joint	Monotonic/ Cyclic testing Simplified strength model	[36]
subjected to monotonic and cyclic loading			

Table A2. Continued...

Title	Type of connection	Methods	Reference
A reversible connection for robotic assembly of timber structures	Timber connection Robotic machining	Monotonic shear test	[37]
Shear performance of a novel non-metallic crosslaminated timber wall-to-wall connection using doubledovetail mortise-tenon joint	Double dovetail Mortise -Tenon	Monotonic/cyclic loading test Simplified capacity and stiffness model	[38]
Robotic Connections: Customisable Joints for Timber Construction	Mortice and tenon	Design proposal of traditional japanese woodcraft	[39]
Technical Performance of innovative dovetail massive timber board slabs	Timber dovetail lamination	Panel testing to fire resistance and soundproof qualities	[40]
Influence of the connector shape parameters in the structural behaviour of the adhesive- free timber floor panels	Carpentry joints	Panel design proposal Bending and rollin shear test.	[41]
Design for adaptability, disassembly and reuse – A review of reversible timber connection systems		Literature review	[42]
An Innovative Connection System for CrossLaminated Timber Structures	X-Rad	Monotonic/Cyclic test Simplified capacity and stiffness model	[43]
Mechanical behaviour of multi-panel cross laminated timber shear-walls with stiff connectors	Sloted joint Spline joint Half-lap joint	Joint shear tests Monotonic test	[44]
System Connector “Double Dovetail Tenon”—A Wood–Wood Based Alternative for Connecting CLT-Elements	Double dovetail tenon	Bending test according to EN 26891 Finite element model	[45]
Proposing new adhesive-free timber edge connections for cross-laminated timber panels: A step toward sustainable construction	Dowell connection DW connection	Finite element modeling on ABAQUS Monotonic load bending test	[46]
Design considerations for robotically assembled through-tenon timber joints	Interlocking wood connections	Joint insertion test	[47]
Construction test of a folding timber bridge	Hinge plate connection	Recording of prototype construction and transport process	[48]
Vertical and shearing performance of kumimono used in traditional wooden structures	Kumimono connection	Compression, moment and shear testing	[49]
Ring Connector: A New Connection System for Prefabrication and DFD in CLT Structures	Ring connectorMultidirectional (timber-to-timber / timber-to-concrete)	Experimental test	[50]

A.3 Experimental investigations of wood and wood-based composites

Table A3 summarizes the experimental investigations of the mechanical properties of wood and wood-based composites cited in Section 1 of the manuscript.

Table A3. Experimental investigations of the mechanical properties of wood and wood-based composites.

Reference	Species / material	Specimen type	Test method	Evaluated property	Main result	Standard / strength class
Yang et al. (2008)	Douglas-fir and Japanese cedar lumber and structural glulam	Visually graded sawn lumber (160 Douglas-fir and 138 Japanese cedar pieces) and structural glulam made from the graded laminas	Static three-point bending; ultrasonic-wave and transverse-vibration non-destructive tests	Static and dynamic MOE, MOR (bending strength), wood density	Static MOE 7.3–20.8 GPa (Douglas-fir) and 8.0–16.4 GPa (Japanese cedar), CoV 10–23% within each visual grade; the transverse vibration test is a better non-destructive method of evaluating sawn lumber; density alone could not accurately forecast MOE and MOR	CNS 14631 (visual grading)
Verma et al. (2014)	Bamboo (Dendrocalamus strictus) laminae and bamboo–epoxy laminates, compared with woods and wood-based composites	Laminae and laminates of Types A [0/0/0/0/0], B [0/45/0/45/0] and C [0/90/0/90/0]	Tensile, compressive and flexural tests	Strength and modulus in tension, compression and flexure	Flexural strength of Type C laminates 105.7 MPa vs 128.4 MPa for Type A (about 18% lower); compressive strength of hardwood and softwood species compiled from the literature, at 12% moisture content: 24.8–69.5 MPa	ASTM D3039; ASTM D3410; ASTM D7264
Bucci et al. (2017)	Iroko solid timber for shipbuilding	Solid timber strips and scarf-jointed strips	Tensile and three-point bending tests	Tensile and bending strength, MOE, density	Characteristic bending strength 71.7 MPa, mean bending MOE 14,208 MPa and characteristic density 553 kg/m^3; the comparison of these values with the EN 338 requirements gives Iroko the strength class D40	EN 408; EN 384; class D40 per EN 338
Corigliano et al. (2017)	Glued laminated Iroko timber	Three-layer laminates with and without scarf joints in the outer layers; four-layer 0/±45/0 laminates	Three-point bending tests	Bending strength, bending and shear moduli	Scarf joints reduce the characteristic bending strength by about 33% (74.4 to 49.8 MPa) while the bending and shear moduli remain unchanged; attributed to the glue bond line	EN 408
Lopez-Anido et al. (2003)	CCA-treated southern yellow pine piles repaired with FRP composite shields	Full-size 9 m class B piles, pre-damaged (about 60% cross-section loss), repaired with FRP shield and cement grout or steel shear connectors and polyurethane grout	Three-point bending tests	Load-deformation response, slip, strain distribution, ultimate bending moment capacity and mode of failure	The pre-damaged pile repaired with the FRP shield and cement-based grout exceeded the bending capacity of a reference pile; the repair with steel shear connectors and polyurethane grout did not fully restore it	ASTM D25 (pile class B); ASTM D1036 (as a guide)

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