Seismic Protection Technologies

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Abstract. Taller timber buildings (TTBs) offer sustainability benefits but pose unique seismic challenges. The following chapter reviews state-of-the-art seismic protection technologies (SPTs) for TTBs, including low-damage self-centering systems, post-tensioned systems, supplemental damping systems, passive and active control systems and base isolation. It discusses the principles, applications, and future challenges of each technology. While significant progress and innovative solutions have been achieved, outstanding challenges include scaling the technology, optimizing cost-effectiveness, and managing interactions between structural and non-structural elements to enhance functional recovery, damage limitation, and acceleration reduction. By examining current practices and future directions, this review facilitates a broader understanding and implementation of SPTs, promoting the sustainable growth of TTBs in seismic-prone regions.

Keywords: Seismic protection technologies · Low-damage and self-centring · Post-tensioned systems · Supplemental damping systems · Passive and active control · Base isolation

1 Introduction

Timber has long been a material of choice in construction due to its renewability, excellent strength-to-weight ratio, and aesthetic appeal. In recent years, timber has grown in popularity, driven by the growing emphasis on sustainable construction practices and innovative mass timber products. Among these developments, the construction of taller

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timber buildings (TTBs) has emerged as a significant innovation, showcasing advancements in engineering and design. While the adoption of TTBs offers numerous benefits, including reduced carbon footprints and enhanced architectural versatility, their performance under seismic conditions presents unique challenges that necessitate further exploration.

Historically, timber buildings have demonstrated varying levels of seismic resilience, influenced by factors such as construction techniques, material properties, and design standards. Traditional timber structures often relied on flexibility and low mass to withstand seismic forces, yet they frequently suffered irreversible damage that was difficult to repair. Modern engineering approaches have introduced new opportunities for designing timber buildings to meet stringent seismic performance requirements, particularly in Serviceability Limit State (SLS) and Ultimate Limit State (ULS) scenarios. However, as urbanization accelerates and the demand for mid to high-rise timber structures increases, addressing the seismic demands and challenges associated with TTBs becomes paramount.

The inherent characteristics of timber budlings, while beneficial in many aspects, also introduce specific complexities for seismic design. Their lightweight nature, while beneficial in reducing inertial forces, necessitates careful consideration of dynamic properties to avoid potential amplification of accelerations during seismic events. Furthermore, integrating innovative materials and hybrid systems has added layers of complexity, requiring interdisciplinary collaboration and development of new devices and design methodologies.

Following the afore-discussed challenges, Seismic Protection Technologies (SPTs), such as low-damage self-centering systems, post-tensioned systems, supplemental damping systems, and base isolation technologies, have been adapted and developed to enhance the resilience of timber buildings. These technologies focus on minimizing structural and non-structural damage, improving energy dissipation, and enabling self-centering behaviour after seismic events. Despite significant progress, challenges remain in scaling these solutions for TTBs, optimising cost-effectiveness, and addressing the interactions between structural and non-structural elements. Therefore, this chapter explores the state-of-the-art on seismic protection technologies for TTBs, highlighting both established and emerging solutions. It also identifies critical difficulties and research gaps, including the need for comprehensive empirical data, refined design parameters, and the development of performance-based frameworks tailored to contemporary timber structures. By examining current practices and future directions, this study aims to contribute to the broader understanding and implementation of SPTs, facilitating the growth of TTBs in seismic regions. In addition to discussing the dynamic behaviour and energy dissipation principles of TTBs equipped with SPTs, this paper presents an overview of various seismic protection technologies and their practical applications. The discussion is further contextualized through a review of current trends, advancements, and outlook, setting the stage for future innovations in this fast-evolving field.

2 Concept and Methodology of Seismic Protection Technologies

The recent shift in contemporary seismic design—from focusing solely on structural safety to prioritizing damage limitation and full functional recovery with an emphasis on performance-based loss design - was both highly anticipated and necessary. Although significant research in recent years has focused on the structural safety of timber buildings - particularly on connections, lateral load-resisting systems, design codes, and construction techniques - SPTs are an emerging area in timber engineering design aimed at further enhancing their resilience.

Generally, connections play a crucial role in timber structures by transferring forces between members and dissipating energy. When designed to yield, these connections are susceptible to significant non-linear deformations, and non-recoverable damage.

Consequently, SPTs should prioritize reducing the demand on connections and prevent non-linear deformation and unrecoverable damage, ensuring all structural elements and connections to behave elastically under strong ground motions. Additionally, to guarantee financial justification for their implementation in TTBs, these technologies should also minimize large accelerations in upper stories, which are recognised as a primary source of damage to non-structural elements.

In recent years various seismic protection technologies have been developed and are being studied numerically and experimentally. In this sense, seismic protection technologies and devices for TTBs can be broadly categorised into five major groups: *Low-damage and self-centring systems*; *Post-tensioned systems*; *Supplemental damping systems*; *Passive and active control systems*, and *Base isolation systems*. An illustrative overview of the types of SPTs and the number of original publications, which were found (per type and year), is presented in Fig. 1. Although a clear boundary between low-damage self-centering solutions and post-tensioned systems, as well as motion dependant and some passive control systems, could not be easily established, it is evident that the former constitute the majority of publications. Nonetheless, in recent years, there has been an overall increase in research, particularly in the areas of supplemental damping and isolation technologies. However, hybrid or combined approaches are still lacking.

As fundamental principles in SPTs, three key approaches can be identified: i) increasing damping ii) increasing flexibility (elongating the fundamental vibration period) and iii) hybrid approach which combines the two afore mentioned principles.

Although shortening the period usually means greater acceleration, it leads to smaller displacements, and therefore lower drifts, which is definitely an advantage for timber buildings, as structural damage correlates more strongly with displacement and interstorey drifts than with forces [1]. Following, shifting the fundamental vibration period to a large value to limit the amount of transferred force to the building, results in higher displacements and much smaller accelerations of the superstructure, which protects the acceleration-sensitive content in the building. In spite of the increased displacement demand during an earthquake, most of the demand should be met by the SPT system, while the superstructure typically shows much smaller peak floor accelerations and so less non-structural damage, which in contemporary construction constitutes up to 90% of the building cost. However, at this point it is important to note that accelerations, even though highly related to non-structural damages, are not generally been studied and picked up to such an extent in the scientific literature.

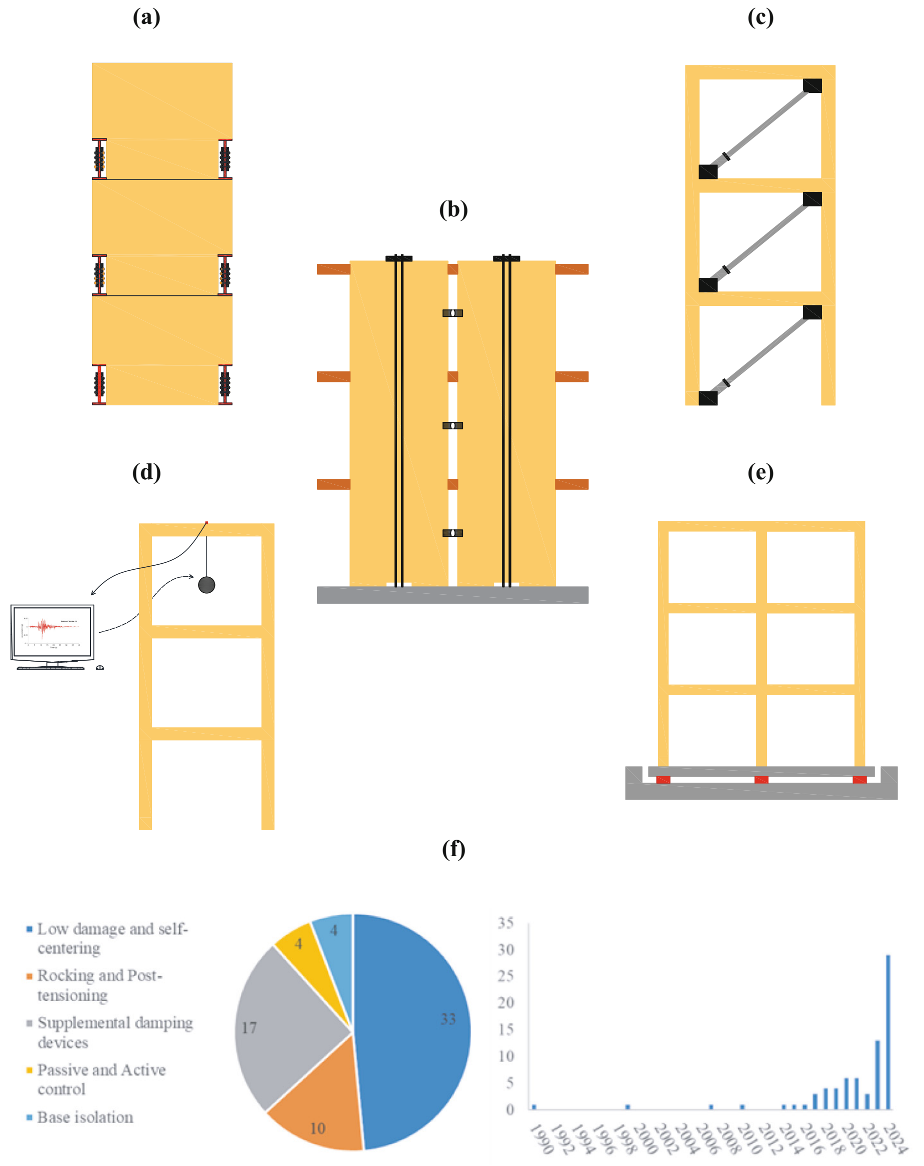

Fig. 1. Types of SPTs for TTBs: (a) Low-damage and self-centring e.g. RSFJ walls; (b) Post-tensioned systems e.g. PT walls; (c) Supplemental damping e.g. Viscous dampers; (d) Passive and Active control e.g. Active mass damper; (e) Base isolation e.g. Elastomeric isolation; (f) Number of recent research publications per SPT type and total number of publications per year.

Furthermore, it is argued that timber buildings would not benefit from additional damping due to their high effective damping ratio, which correlates with their inelastic behaviour associated with structural damage, primarily connections. Therefore, the main principle that should be followed for the implementation of SPTs into the design process is to reduce or exclude the energy dissipated by the inelastic behaviour of the structure (high damage and failure of connections). Finally, in such a way their economic investment would be easily negotiable.

3 Types of Seismic Protection Technologies

3.1 Low Damage and Self-Centering Systems

The systems concepts are based on automatic mechanisms for returning the main irreplaceable parts of the structural systems to their initial positions after earthquakes. In this regard, to achieve the self-centring capacity of TTBs, several innovative systems and models have been proposed and studied, experimentally and numerically. Table 1 briefly summarises the state-of-the-art for low-damage and self-centring systems and solutions that are included and discussed in this chapter.

Steel and abrasive-resistant Slip-Friction Devices (SFDs) for mass timber structures, with prestressed bolts, were initially proposed by Loo et al. [2]. The innovative hold-down devices consist of steel plate encased in the structural element and an envelope of two abrasive-resistant steel plates, which form two shear planes held together by prestressed bolt-springs. The results of cyclic tests showed a high energy dissipation capability without pinching and a characteristic flag-shaped hysteresis. A further step ahead towards an improved low-damage connection solution was the adaptation of the system into a damage-free self-centring solution for CLT shear walls – the resilient slip friction joint (RSFJ) introduced by Zarnani and Quenneville [3], which is still being investigated and highly tested for various structural systems and materials. The RSFJ has two middle and two cap serrated plates compressed by a bolt and disc spring system, enabling a high self-centring capacity of the system. The device was furthermore verified by an implementation in a Self-Centring Rocking timber Wall system by Hashemi et al. [4]. In addition, Hashemi et al. [5] used the RSFJ in a hybrid damage-avoidant steel-timber wall systems to prevent residual displacement and minimize damage. Finally, Hashemi et al. [6] utilized RSFJ as hold-downs in rocking CLT walls to reduce the residual displacement and improve the self-centring capacity of the rocking CLT walls.

More recently, Assadi et al. [7] tested the performance of the RSFJ as a low-damage floor connection. The implemented solution significantly improved the seismic performance. It increased the damping capacity, reduced displacement and force demands, and enhanced the overall economical design by reducing the size of wall hold-downs. In addition, Assadi et al. [8] conducted a comprehensive full-scale shake-table test on a 3-story steel structure equipped with different configurations of RSFJs. The results confirmed the reliability and predictability of the RSFJ system in reducing structural damage and ensuring quick reoccupation of buildings post-earthquake.

Solutions based on a similar operating principle to the RSFJ include: the slip-friction moment-resisting connection using screwed-in threaded rods introduced by Hegeir et al. [9] and Self-Centring Timber Brace (SC-TB) by Yousef-Beik et al. [10]. In the former solution, the moment-resisting connection was implemented in CLT beams and columns. Four full-scale tests were conducted, under service loads and destructive cyclic loads. The connection showed high stiffness and moment capacity, with ductile behaviour and

Table 1. Low-damage and self-centring systems literature review.

System type	Relevant research
Shear walls	1. Slip-Friction Connectors (SFC) [2]
	2. Resilient Slip Friction Joint (RSFJ) [3]
	3. Self-Centring Rocking Wall system (SC-RW) [4]
	4. RSFJ as hold-downs in rocking CLT walls [6]
	5. Elliptically profiled CLT walls [11]
	6. Rocking CLT walls with Uplift Friction Dampers (UFD) [12]
	7. High performance rocking timber wall with innovative low-damage floor connections [7]
Post & Beam	1. Hysteretic Performance of Self-Centering Glulam Beam-to-Column Connections [13]
	2. Self-centering timber moment resisting frames [14]
	3. Self-Centring Timber Brace (SC-TB) [10]
	4. Slip-friction moment-resisting connection using screwed-in threaded rods [9]
	5. Timber Beam–Column Connections with SMA Bars [15]
	6. Mass timber frames with timber buckling restrained braces [16]
	7. Glulam frames with dual-tube self-centering buckling-restrained braces [17]
Hybrid and Buildings	1. Hybrid steel-timber wall system using the RSFJs [18]
	2. Self-Centring Steel-Timber Hybrid Shear Wall (SC-STHSW) [19]
	3. Performance of self-centering hybrid damping systems under far-field and near-field ground motions [20]
	Seismic Fragility Assessment of a Balloon-framed CLT Building with Self-centering Hold-down [21]

failure through plastic hinging in the rods. The Self-Centring Timber Brace (SC-TB) was primarily aimed to improve the conventional timber braces. Experimental and numerical studies validate the SC-TB's effectiveness. A comparative study on a four-story building showed that SC-TB outperforms conventional braces in terms of base shear, pinching, and damping. In addition, the SC-TB system demonstrated superior performance with zero residual drift, lower base shear, and no pinching or timber crushing.

To address the limitations of conventional steel–timber hybrid systems Cui et al. [19] introduced a self-centering steel–timber hybrid shear wall (SC-STHSW) system. The proposed system integrates post-tensioned (PT) technology and slip friction dampers to improve both energy dissipation and self-centering capacity. A full-scale experimental test demonstrated its effectiveness by producing a flag-shaped hysteresis curve that indicates strong energy dissipation and minimal residual deformation.

An Uplift Friction Damper (UFD) composed of tension bolts and disc springs combined with an angled abrasive friction interface has been used as a low-damage and energy dissipater connector in rocking shear walls [12]. In the proposed UFD, post-tensioned (PT) rods provide the self-centring response while two angled steel wedges slide on each other to dissipate energy. Ricco et al. [11] proposed an elliptically profiled CLT walls to form a rocking story in multi-story CLT buildings. The system is a rocking soft story based on the elliptical rolling rod isolation, which also reminds of base isolation system. The use of a soft storey as a seismic isolator buffers the upper stiff portion of the building from ground motions during earthquakes. Two types of connectors with different restriction mechanisms, No-Slip Traction Rolling (NSTR) and Slip Friction Rocking (SFR) connection, were tested to assess the lateral behaviour of the elliptical walls, both types exhibited similar rotational capacities. Finally, an equivalent lateral force procedure, was proposed, for effectively estimating the seismic demands for CLT buildings with elliptical rocking walls, and simplifying the design by using a static force procedure to approximate the complex dynamic effects, providing a practical tool for design.

3.2 Post-Tensioned Systems

Post-tensioned timber technology can provide increased strength and stiffness for mass timber seismic load resisting systems while also providing energy dissipation and re-centring capabilities for large lateral deformation without significant residual damage. The state-of-the-art research and initial implementation of the post-tensioned timber systems to real world construction projects, which gained in popularity after the 2011 Christchurch Earthquake, was reported by Granello et al. [22]. Other key research projects and publications are listed in Table 2.

The response has been extensively studied on full-scale structures as part of the University of Canterbury's (Department of Civil Engineering) project in New Zealand reported in Newcombe et al. [23], Natural Hazard Engineering Research Infrastructure Tall Wood Project (NHERI-TWP) described in Pei et al. [24], and the Seismology and Earthquake Engineering Infrastructure Alliance of Europe Project (SERA) described by Pampanin et al. [25].

The research findings show that the controlled rocking mechanisms of elastic post-tensioning provide self-centring action to eliminate residual drifts, while additional dissipative devices, such as replaceable steel fuses, increase the damping and reduce lateral displacements of multi-storey buildings. Although no severe structural damage was observed, non-structural damage occurred even at low levels, partially caused by floor accelerations. The previous findings were in line with recently conducted shake-table tests on a 10-story building, which demonstrated that such a building can withstand design based and maximum considered earthquake level events repeatedly without notable residual drift, structural member damage, or connection damage. The building exhibited only moderate non-structural damage that would be repairable, meeting the intended design goals [26]. Consequently, improving the detailing of the connections and the sacrificial ductile elements between structural and non-structural elements was highlighted as a key opportunity to enhance the resistance [25, 26]. Furthermore, the interaction between structural and non-structural elements under seismic loading requires

Table 2. Post-tensioned systems literature review.

System type	Relevant research
Shear walls	1. Laminated veneer lumber (LVL) walls [30]
	2. CLT walls [27]–[31]
	3. Single and coupled Post-Tensioned CLT (PT-CLT) walls [32]
	4. Post-Tensioned CLT Shear Walls with Energy Dissipators [33]
	5. Higher-mode effects of rocking mass timber walls with controlled overturning moments [28]
Post & Beam	1. Beam-column connections [13–34]
	2. Frames [29–35]
	3. Post-tensioned glulam frame [36]
	4. Fragility functions for low-damage post-tensioned timber frames [37]
Hybrid and Buildings	1. Two storey Pres-Lam timber building [29]
	2. SERA Project - Integrated Low-Damage Building System [25]
	3. Vertical steel ties for stiffening earthquake-resistant CLT buildings [38]
	4. 10 - story mass timber building [24, 26, 39]

further considerations to achieve a holistic design [27]. This should include refined low-damage design methodologies and technologies, ensuring their cost-effectiveness and widespread adoption [25]. In addition, higher mode shapes influence and modifications of current design principles were emphasised as a further research area [26–28]. Furthermore, research on the stiffness of connections and long-term performance data is still lacking and limited, health monitoring, environmental effects and maintenance of the post-tensioned steel tendons also require further investigations [22]. In this sense, research is needed on the effects of anchorages in highly stressed beam-column joints to prevent issues like column fractures or failures [29].

Recent numerical research by Matteoni et al. [37] developed a framework for fragility functions evaluation of low-damage post-tensioned timber frames, using nonlinear static and time history dynamic analyses and a Python-based parametric workflow.

In the area of mass timber shear wall platform type buildings stiffened with vertical steel ties or tension rods, as reported in Keskisalo [40], Gräfe et al. [41] and Pacchioli et al. [38], further research and development is needed for a successful implementation of the technology in seismic prone areas. An emphasis is in investigating the coupling of these systems with ductile devices to dissipate energy and reduce inertial forces and minimise possible brittle failures.

Finally, an extensive review of recent progress of post-tensioned and self-centering systems for mass timber structures can be found in Ugalde et al. [42] and Chen et al. [43].

3.3 Supplemental Damping Systems

Seismic protection through supplemental damping aims at decreasing the structural demands and consequently inter-story drifts while potentially adding stiffness in the structural systems by increasing inherent damping dissipation through the addition of supplemental devices called dampers. These devices can increase the equivalent viscous damping and are activated by: (i) displacement (e.g. metallic dampers, hysteretic devices, friction dampers); (ii) velocity (e.g. viscoelastic dampers (VEDs) or viscous fluid (VF)), or (iii) motion (e.g. tuned mass dampers).

The first reported study on the subject of supplemental damping in timber structures was carried by Filiatrault [44], which analytically predicted the seismic response of friction damped shear walls. Nonetheless, the study presented only analytical results and did not include experimental validation of the proposed solution. Since then, significant progress and research have been conducted. A summary of recent state-of-the-art research can be found in Table 3.

Table 3. Supplemental damping systems literature review.

System type	Relevant research
Displacement dependant dampers	1. Perforated steel structural fuses in mass timber lateral load resisting systems [57, 58] 2. Highly ductile hold-down with adaptive stiffness for timber seismic bracing walls [59] 3. Timber frame with novel energy-dissipation joints [60] 4. Light wood shear wall structures with slotted-bolted dampers [61] 5. Superelastic SMA Dowel Connections for Braced Timber Frame Applications [62] 6. Timber Beam-to-Steel Column Connection with Replaceable U-Shaped Fuses [63] 7. Friction-based connectors with wooden dowels for timber shear walls [45]
Velocity dependant dampers	1. CLT shear walls with novel dissipative angle brackets and hold-downs [51] 2. Dissipative angle brackets and hold-downs with soft-steel and rubber for CLT buildings [52] 3. Sound-insulated joints and dynamic behaviour of CLT structures [64] 4. Pre-damaged Two-Story Traditional Timber Frame reinforced using Viscoelastic dampers [53]
Motion dependant dampers	1. High-Rise Hybrid-Timber Building: A Comparative Study [55]
	2. Tuned Liquid Column Damper (TLCD) for Taller Timber Buildings [56]
Hybrid approach	1. Low-cost and sustainable timber-based energy dissipation system with recentering ability [54]

The studies showcase advancements in hybrid steel-to-timber dissipative connections and displacement dependant energy dissipation systems. The presented innovative devices, on one hand enhanced seismic performance by introducing higher ductility, whereas on the other reduced total costs. The hybrid steel-to-timber approaches demonstrated stable performance and excellent ductility, while SMA fasteners show additional self-centering potential but need further research. Finally, a recent study on friction-based supplemental damping connectors with wooden dowels for timber shear walls, tested on a shake table by Wakashima et al. [45], reports improved seismic performance by providing high damping and minimal stiffness/strength degradation - connectors maintained their performance over time. Furthermore, the results highlight the potential of these dissipative connectors, especially in regions prone to repeated seismic events.

Supplemental velocity-dependent damping systems, such as viscoelastic-viscous, or tuned mass dampers, have been for mass timber structures, mostly studied through numerical research. Although, numerical analyses have demonstrated the effectiveness of velocity-based visco-elastic dampers in controlling the floor accelerations of such structures (e.g., [46–48]), experimental research on applying passive viscous or viscoelastic damping to mass timber structures is currently lacking. It has only been reported on light wood-frame shear walls by Dinehart et al. [49, 50], demonstrating their efficiency. In addition, Chen et al. [51] introduced dissipative angle brackets and hold-downs with encased rubber layer, which showed superior lateral performance, including higher ductility and energy dissipation compared to conventional brackets. Damage, depending on the load intensity, was localized at the rubber layer or brackets, with CLT walls exhibiting excellent deformation capacity and an increased inter-story drift ratio. Furthermore, full-scale shaking table tests of a complete building confirmed the effectiveness of these dissipative connections under various ground motions, when compared to traditional solutions [52]. Finally, Yi et al. [53] investigated the seismic performance of traditional timber frames, focusing on the effectiveness of VEDs in recovering the seismic performance of earthquake-damaged structures. The full-scale shake-table tests showed that VEDs significantly improved the seismic performance, reducing deformation and enhancing energy dissipation.

Low-cost and sustainable hybrid system approaches, such as the timber-based energy dissipation system with recentering ability - Dovetail with Springs (Dove-SP), which uses two timber slabs that slide against each other, restrained by a dovetail joint and recentred by low-cost steel springs, as presented by Tsiavos et al. [54], offer promising solutions for mitigating both residual sliding displacement and impact accelerations, deserving further research.

Motion-dependent supplemental damping systems for TTBs have been under-investigated, both numerically and experimentally. A recent study by Chapain et al. [55] presents a dynamic analysis of a 42-story hybrid-timber building and investigates the performance of three motion-dependent damping devices: (i) pendulum pounding tuned mass damper (PTMD), (ii) tuned mass damper inerter (TMDI), and (iii) tuned mass damper (TMD). The study evaluates the vibration reduction capability of these devices under filtered white noise and variable frequency sinusoidal excitations. The results show that the pendulum PTMD has higher performance in reducing peak accelerations, base shear, base moment, and inter-story drift ratio compared to TMD and TMDI. Meanwhile, Çelebi [56] examined the use of Tuned Liquid Column Dampers (TLCDs) in multi-story timber buildings, highlighting their ability to dissipate energy and improve structural stability. TLCDs offer adaptability, low maintenance, and potential fire suppression benefits Finally, it should be mentioned that the former motion-dependent systems could also be partially classified as passive-active control systems, as a clear boundary between such supplemental damping devices and passive-active control systems is not distinct.

3.4 Passive and Active Control Systems

With the new challenge for designers to accommodate higher demand requirements, especially in SLS, innovative dissipating devices and self-centering systems have been combined in mass timber structures as active or passive control systems, as listed in Table 4. Control system can minimize damages to structural and non-structural elements when providing enough structural performance. The systems are designed to absorb and dissipate energy during seismic events, of various magnitudes, thereby reducing the impact on the primary or secondary structure. However, one significant challenge with traditional systems, if they are not combined with other technologies, is residual deformation, which complicates the reuse or reoccupation of structures after major earthquakes. In addition, unlike steel structures, which have established some guidelines for integrating control systems, mass timber structures require more tailored and material specific solutions. The absence of standards or implementation methods for these systems in TTBs highlights a critical gap in the field.

Table 4. Passive and Active control systems literature review.

System type	Relevant research
Inerter approach	1. Rocking timber buildings equipped with inerters [65] 2. Inerter-equipped rocking structures [66] 3. Fluid inerter-based vibration control [67]
Semi-Active approach	1. Timber Frame equipped with Semi-Active Resettable Devices [68]
SMA approach	1. Multi-outrigger tall-timber building: Using SMA-based damper and Lagrangian model [69] 2. CLT structure with shape memory alloy-based semi-active tuned mass damper (SMA-STMD) [70] 3. Pre-strained shape memory alloy-tuned mass dampers for CLT floor vibration mitigation [71]

Seismic performance of rocking post-tensioned timber buildings with rocking walls, combined with inerters to control rotation amplitude and suppress higher-mode effects were investigated by Thiers-Moggia and Málaga-Chuquitaype [65, 66]. This combination of approaches significantly improved the seismic performance by reducing floor accelerations. Nonetheless, further experimental research is needed and recommended to optimize inerter design and validate their effectiveness across various seismic conditions and structural configurations, as part of ERIES-TRUST-Truly resilient timber buildings (2024). In addition, data drive approaches to evaluate intensity measures and develop simplified regression models or parametric models for predicting peak floor accelerations, drift demands and displacements of TTBs, as employed by Junda and Málaga-Chuquitaype [72] or Demirci et al. [73], can serve as entry points for future development and implementation of more robust active or semi-active control systems or technologies such as Magnetorheological Fluid Dampers [74], active mass dampers [75] or Fluid inerter-based vibration control systems [67].

Other studies by Das and Tesfamariam [69], Yan et al. [70] and Jiang et al. [71], investigated shape memory alloy-based (SMA) passive and semi-active dampers for CLT structures, demonstrating their effectiveness in reducing seismic vibrations by using the temperature-dependent properties of SMAs. However, further research, for these technologies is needed to optimize the design process and potentially integrate them with other SPTs.

Finally, a timber frame equipped with a semi-active experimentally validated resettable tendon device to reduce seismic response was implemented by Franco-Anaya and Iqbal [68]. The research involved analytical studies of a four-story timber frame subjected to seismic excitations and controlled by the semi-active device, which greatly improved the structural performance under eight different ground motions.

3.5 Base Isolation Systems

Although light-frame timber buildings have been deemed to perform well during strong earthquakes, due to their low mass and ability to deform inelastically without collapsing [76], the Northridge Earthquake's consequences revealed that light-frame timber buildings are prone to significant damage when subjected to strong ground motions. The inelastic response of such buildings is generally linked with significant structural and non-structural damage that may be costly to repair. Filiatrault et al. [77] stated that large inter-story drifts are the primary cause of significant damage. In order to limit the excessive inter-story drifts in the horizontal direction, base isolation systems, elastomeric bearings with low lateral stiffness or sliding isolation bearings with relatively low level of friction, can be implemented between the foundation system and superstructure to shift the fundamental vibration period of the building and reduce inter-story drift [76–78]. In spite of being common for concrete and steel structures, installing base isolation systems in wood frame buildings can be challenging, as noted by Symans et al. [76]. This is because the floor diaphragms often lack sufficient in-plane stiffness to effectively transfer forces to the base isolation system, while ensuring uniform motion across all bearings. Additionally, in the case of low-friction sliding isolation bearings, the lightweight nature of wood frame buildings may lead to undesirable sliding during strong windstorms. The low mass can also require the use of slender and potentially unstable elastomeric bearings. Despite these practical challenges, recent limited studies, listed in Table 5, suggest that base isolation has the potential to improve the seismic performance of wood frame and contemporary mass timber buildings.

From a historical perspective, the first study by Delfosse [79], demonstrated, through an example design, that it is feasible to utilise an elastomeric base isolation system for a single-story wood-framed house. Following, Reed and Kircher [80] discussed a seismic retrofit study on a five-story wood-frame building using two different isolation system

Table 5. Base isolation systems literature review.

System type	Relevant research
Light timber frame	1. Half-Scale Base-Isolated Wood Frame Building [78] 2. Base-isolated and base-fixed Ancient timber buildings in hanging-wall/footwall Earthquakes [84] 3. Cost-efficient isolation system for light frame timber buildings [85] 4. Impact-resilient seismic isolation system [86]
Cross-laminated timber	1. Predictive models for mid-rise base-isolated CLT buildings in Chile [87] 2. Performance of CLT Structures with base isolation [88]

configurations: one with elastomeric bearings and the other with flat sliding bearings. Sakamoto et al. [81] presented an experimental and analytical study of a two-story light-framed wood building supported on a base isolation system. The building was constructed at the University of Tokyo for in-field (not laboratory) experimental testing. Furthermore, in 1988, a base isolation system was implemented within a two-story light-frame wood house in Montreal, Canada [82]. Finally, Zayas and Low [83] discussed retrofitting a four-story wood-framed residential building, implementing sliding friction pendulum system (FPS) bearings.

In more recent studies, J. W. Van de Lindt et al. [78] presented the issues related to the application of base isolation in light-frame wood buildings by conducting shake table tests on a half-scale, two-storey base-isolated (with FPS) residential building. The study results demonstrated that FPS bearings offer a technically viable passive seismic protection system for light-frame wood buildings in high seismic zones. Seismic performance of base-isolated and base-fixed Ancient timber buildings in hanging-wall/footwall earthquakes was studied by Ou and Wang [84]. The study found that base isolation greatly reduced the response of the four models, whereas the relative peak displacement decreased by more than half compared with the base-fixed model, indicating that isolation improved the overall seismic performance. In addition, Quizangha et al. [85, 86] investigated a 3-story Light Frame Timber Building (LFTB) with Impact-Resilient Double Concave Frictional Pendulum (IR-DCFP) isolators on a shake table. The IR-DCFP isolators provided effective seismic protection for the constructed LFTBs. Furthermore, the experimental and numerical results confirm the system's performance and highlight the importance of accurate damping modelling. Finally, despite the extreme excitation, the superstructure remained in the elastic range, with peak acceleration ratios (i.e., peak floor acceleration to peak ground acceleration) not exceeding 0.75 and story drift ratios smaller than 0.52% in most cases.

Despite only being limited to numerical studies, the implementation of base isolation in mass timber multi-storey structures promises to be a viable type of SPT for improving the seismic performance and structural safety. With that in mind, two types of friction pendulum isolators and an elastomeric isolator's performance were compared by modelling 3-, 6- and 12-storey CLT buildings in Poshtiban [88]. The effect of the aspect ratio of the CLT panels on the seismic performance was also studied. The study concluded that all three isolation systems significantly reduce base shear, acceleration, and interstory drift, with friction pendulum systems generally outperforming rubber isolators. The effectiveness of these systems varied with the number of stories and ground motion types. The panel aspect ratio plays a crucial role in the seismic performance of non-isolated CLT buildings, but it is less influential in base-isolated buildings. Furthermore, Medel-Vera et al. [87] presented predictive models for the seismic behaviour of mid-rise, base-isolated CLT buildings by performing nonlinear dynamic analyses on four building models. The study focuses on the fundamental period of vibration, a parameter that must be selected in the early stages of a seismically isolated building's design process. It concludes that selecting the fundamental period of vibration significantly impacts potential economic and environmental losses in seismically isolated CLT buildings. Therefore, this selection should consider resilience and sustainability parameters in addition to the technical aspects.

4 Challenges and Outlook

Considering the afore-discussed earthquake-related challenges of TTBs, holistic multi-hazard high-performance seismic protection solutions, which address both earthquake functional recovery with damage limitation and vibration and acceleration reduction, under various load amplitudes, should be explored as promising potential avenues to improve the structural resilience and viability of such structures. The primary role of TTBs SPTs should be transferring forces and accommodation of displacements between structural and non-structural elements, as well as ensuring appropriate dynamic behaviour, ductility with additional energy dissipation under different load amplitudes and additional self-centering without significant residual displacement. Moreover, the exposure of such seismic protection technologies to high amplitude cyclic loads should not be a dominant issue related with stiffness loss and irreversible residual damage. Following, hybrid systems, which combine more than one protection mechanism, offer a promising alternative. These systems provide greater flexibility and responsiveness to various intensity earthquake events, primarily by using the strengths of different approaches. As such, hybrid systems represent a forward-looking solution for enhancing the seismic performance of TTBs. Finally, considering construction techniques and cost competitiveness, SPTs assembly and installation procedures should adapt to contemporary mass timber building techniques and practices.

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