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ADVANCED SEISMIC-RESILIENT CONNECTION FOR MODULAR MASS TIMBER STRUCTURES

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ABSTRACT: Prefabricated Modular Mass Timber (PMMT) construction is becoming increasingly popular among engineers and developers for multi-story buildings due to Cross Laminated Timber's (CLT) inherent strength, stiffness, and prefabrication potential. These buildings consist of prefabricated volumetric modules assembled on-site, offering consistent quality and sustainability advantages over traditional construction methods. Past studies revealed that conventional connections, such as wall-to-floor hold-down brackets and shear connectors with nails and screws, do not meet the requirements for seismic resilient design. This paper presents the seismic performance of a 5-storey PMMT building incorporating an advanced seismic resilient wall-to-floor connection at intermediate levels of a PMMT building. The numerical model developed in ETABS was evaluated using Response Spectrum Analysis (RSA) followed by Nonlinear Time History Analysis (NLTHA), and the seismic performance of the building with the proposed connection was compared with a base-isolated structure. Results indicated that implementing the proposed connection significantly reduces the force demands on PMMT components, enhancing seismic response with acceptable ductility in the system. Additionally, the system displayed effective energy dissipation while exhibiting full self-centering behaviour. The findings of this research revealed that the proposed connection could be an ideal solution for PMMT buildings.

KEYWORDS: Cross-laminated timber, prefabricated modular mass timber (PMMT), cross-laminated timber (CLT), resilient, ductility, numerical model.

1 INTRODUCTION

In the global effort to combat climate change and reduce carbon emissions, the construction industry is exploring innovative materials and methods. Mass timber construction has emerged as a promising alternative to traditional carbon-intensive building materials, offering a sustainable solution that can significantly lower the carbon footprint of buildings [1]. Mass timber products, particularly Cross Laminated Timber (CLT), have gained recognition as high-performance building materials. These engineered wood products exhibit exceptional in-plane and out-of-plane stiffness, making them ideal for use as prefabricated wall and floor panels, paving a pathway for modular construction [2].

In a Prefabricated Modular Mass Timber (PMMT) construction, the prefabricated wall and floor panels are manufactured and assembled off-site as volumetric modules and transported to the construction site, where the modules are stacked together to form a larger, permanent building. The off-site fabrication of these modules in controlled environments ensures consistent quality, optimizes resource use, and contributes to a more sustainable construction process with limited waste [3, 4]. Despite the many benefits of PMMT construction, traditional connections used in PMMT construction do not fulfill the requirement of seismic resilient design as they must yield to dissipate energy during earthquakes, resulting in irreversible damage and making the system vulnerable to aftershocks. As the industry continues to advance, there is a pressing need to develop innovative connection solutions that can overcome these limitations and better utilize the unique properties of mass timber in modular construction. To address these shortcomings, this study proposes a novel seismic resilient connection specifically designed for PMMT construction. This innovative approach aims to improve the seismic performance of PMMT buildings while preserving their structural integrity and minimizing post-earthquake damage.

1.1 SHORTCOMINGS OF EXISTING WALL-TO-FLOOR CONNECTIONS IN PMMT CONSTRUCTION

Recent studies conducted on a series of shake table tests have revealed that CLT PMMT buildings constructed with prefabricated CLT panels are relatively stiff, and the ductility and energy dissipation in the system are solely provided by the connection between the prefabricated CLT panels [5-7]. Additionally, the SOFIE project also reported a floor acceleration of 3.8g at the upper level (7th level) of the building due to the stiff nature of the building. Such high acceleration could lead to serious injuries and fatalities to the building occupants. Thus, implementing strategies to reduce floor accelerations was recommended. Moreover, a quasi-static experimental test on a two-story CLT house also revealed that a ductility factor of 3.0 can be achieved with conventional

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connections. However, the reduction in stiffness and strength could compromise the structural integrity of the system, making it vulnerable to aftershocks [5-7].

Van de Lindt et al. conducted shake table tests on a full-scale two-story CLT house to investigate shear wall performance with varying aspect ratios [8]. Results from the test revealed that while the structure managed to withstand a high-intensity earthquake (1.52g), low-aspect-ratio wall panels failed in shear, exhibiting a sliding mechanism. Nails and the hold-down brackets sheared to dissipate the seismic-induced energy in the system, causing irreversible damage to the connections and making it vulnerable to aftershocks [8]. Quasi-static testing by Popovski et al. on a similar two-storey CLT platform structure examined various connection types across different panel configurations [9]. Their findings showed that conventional connections in PMMT buildings achieved ductility factors of 3.0, while walls with low-aspect ratios demonstrated reduced ductility (2.0). The primary failure mode in low-aspect-ratio walls was sliding, causing horizontal nail displacement and shearing consistent with Van de Lindt's observations [8]. These common connection failures are shown in Figure 1.

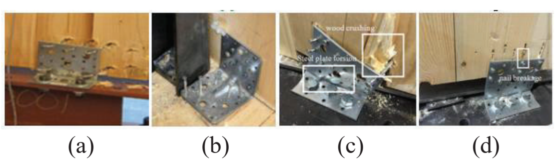

Figure 1: Failure mechanism in CLT connections: (a) Nail withdrawal and yielding [9], (b) nail pull-out failure [5], (c) wood crushing and steel plate torsion, and (d) nail rupture [10].

2 PROPOSED CONNECTION

2.1 INTER-STOREY ISOLATION

Inter-story isolation systems provide notable benefits over traditional base isolation by eliminating the requirements for costly foundation systems with seismic gaps (moats), reducing shear forces between stories, and shielding the isolated section from high seismic forces [11]. Typically, inter-storey isolation is implemented by installing diaphragms on both sides of the isolation layer, which effectively reduces the earthquake forces at the isolation plane without compromising the structural integrity of the upper section. Studies on inter-story isolation have shown that flexibility at intermediate heights reduces seismic demands [12-14]. Zhou et al. (2016) found that buildings with isolation at their lowest levels have minimal roof displacement, indicating that inter-storey isolation is most effective at lower levels [15]. Ryan et al. [16] used Nonlinear Time History Analysis to evaluate six isolation configurations with market-available devices. Both Linear and Nonlinear Response History Analysis demonstrated that isolation at lower levels (first story and base) is most efficient. In contrast, upper-level isolation reduces force demands but decreases system effectiveness, providing only a 30% base displacement reduction. Configurations combining base and mid-height isolation actually increased roof displacement by 30% [16].

2.1.1 ADVANCED SEISMIC RESILIENT CONNECTION

The proposed connection incorporates a friction-based material having a coefficient of friction of 0.3 and high compressive resistance (>26MPa) between CLT floor and wall panels, enabling the CLT floor to slide relative to the CLT wall and dissipate seismic energy. During construction, this material is installed separately on wall tops and floor undersides using countersunk screws, creating a sliding interface as illustrated in Figure 2. This friction isolator functions similarly to reference [17], maintaining consistent strength and stiffness properties. The proposed isolation concept is shown in Figures 2 and 3.

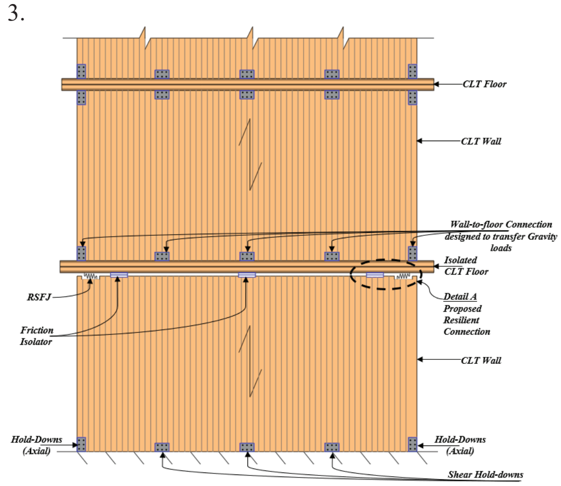

Figure 2: 2D schematics of the proposed floor-to-wall connection in a PMMT building.

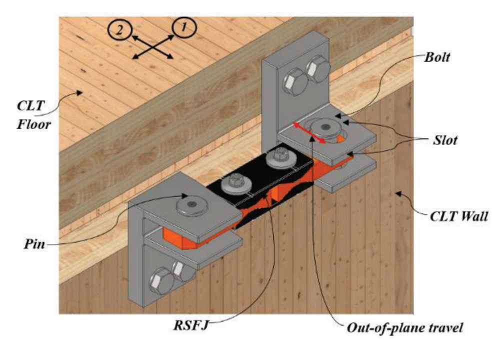

Figure 3: RSFJ connection detail

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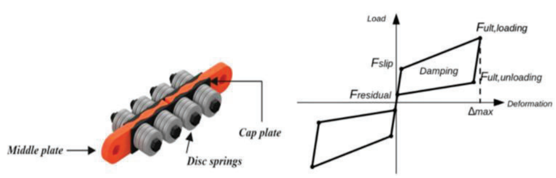
During seismic excitation, energy dissipation occurs through friction between pads positioned on CLT walls and floors, allowing unrestricted bidirectional sliding while accommodating out-of-plane movement through slotted connection plates. The established Resilient Slip Friction Joint (RSFJ) [18] enables floors to self-center as frictional sliding dissipates energy while ridged surfaces and disc springs provide re-centering capability. When force overcomes resistance between clamped plates, middle plates move first, followed by cap plates moving outward until reaching ultimate displacement, where disc springs flatten. The inherent properties of RSFJs provide energy dissipation, full self-centering behavior, and additional capacity through a secondary fuse mechanism for life safety, providing 1.75 to 2 times displacement capacity with reserve force capacity of approximately 1.35 times design displacement, including bolt strain hardening after yield [19, 20], with the assembly and flag-shaped hysteresis shown in Figures 4a and 4b.



(a) (b)

Figure 4: *Resilient Slip Friction Joint (RSFJ): (a) assembly, and (b) flag0-shape-hysteresis [19, 20].*

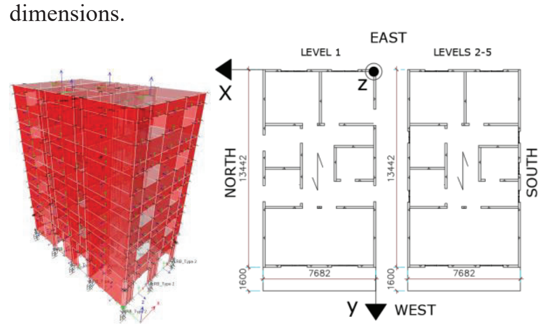
3 METHODOLOGY

3.1 BUILDING ARCHETYPE DETAILS

This study examines the effectiveness of the proposed wall-to-floor connection in mass timber construction through analysis of eight distinct archetypes of a five-story CLT platform-type building. The seismic performance of the system incorporating the proposed connection was compared to a base isolation system employing rubber isolators with nonlinear parameters in U2 and U3 directions at designated wall locations.

A comprehensive 3D numerical model was developed in ETABS [21] featuring a structure with in-plan dimensions of 13.442m × 7.682m, adapted from a previous seven-story design [5], with story heights maintained at 3.1m for levels 1-2 and 3.09m for subsequent stories. The structural elements consist of five-layer (210mm) CLT walls for levels 1-3, three-layer (126mm) CLT walls for levels 4-5, five-layer (210mm) CLT floor panels, and a three-layer CLT roof, all designed according to established guidelines [22]. The CLT panels utilize Machine Stress-graded sawn timber with elastic moduli of 8GPa for longitudinal laminations and 6GPa for transverse laminations. In the numerical model, frictional isolator links were implemented at uniform intervals (1.5-2.0m) along wall perimeters with nonlinear parameters enabled in U2 and U3 directions, while Damper-Friction Spring elements positioned 0.1m from wall edges provide the necessary restoring forces for self-centering, with RSFJ parameters calibrated according to established protocols [20].

The structure's seismic weight distribution is 580kN for stories 1 and 2, 537kN for story 3, 492kN for story 4, and 231kN for the roof. The building is situated on soil type D in Wellington, New Zealand, and is classified as an important level 2 structure. The proposed connection implementation requires a 40mm vertical gap between the wall panel's top surface and the floor's bottom surface, with the re-centering mechanism attached in a pre-defined "U" cut (wall pocket) on the top edge of the wall. Response Spectrum Analysis (RSA) has been adopted to verify the seismic performance of the system, followed by Nonlinear Time History Analysis (NLTHA) to account for analytical variabilities. Figures 5a and 5b illustrates the archetype's 3-dimensional view and in-plan dimensions.



(a) (b)

Figure 5: *Numerical model: (a) 3-D view, and (b) In-plan view*

In ETABS [21], the "Friction Isolator" link elements were modeled to represent the hysteresis behavior of the low friction-based proprietary material. Figure 6 presents 2D elevation views illustrating structural schematics of an isolated building with the implementation of the proposed inter-story isolation connection at various levels of a 5-story PMMT building. Configurations range from isolation solely at Level 1 (a) to complete isolation at all levels (h). Each variation demonstrates how isolation distribution can enhance seismic performance in PMMT buildings. The study examines seismic performance metrics, including base shear, inter-story drift, residual drift, and floor acceleration across different configurations incorporating the proposed wall-to-floor connection.

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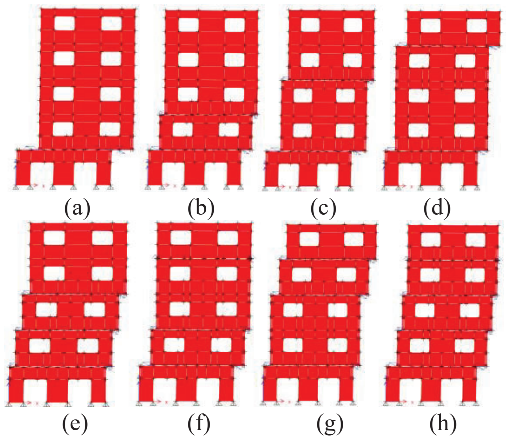

Figure 6: *2D Schematic of the Isolated Buildings: (a) Isolation at Level 1, (b) Isolation at Level 1 and Level 2, (c) Isolation at Level 1 and Level 3, (d) Isolation at Level 1, and Level 4, (e) Isolation at Level 1, Level 2, and Level 3, (f) Isolation at Level 1, Level 2, and Level 4, (g) Isolation at Level 1, Level 3, and Level 4, and (h) Isolation at Level 1, Level 2, Level 3, and Level 4.*

Table 1*: Summary of the case study structures.*

Case study archetype	Device Location	Vertical gap between floors (mm)	Number of RSFJs	Number of Friction Isolators
a	L1 only	40	8	53
b	L1, and L2	40	16	106
c	L1, and L3	40	16	106
d	L1, and L4	40	16	106
e	L1, L2, and L3	40	24	159
f	L1, L2, and L4	40	24	159
g	L1, L3, and L4	40	24	159
h	L1, L2, L3, and L4	40	32	212

Note: L= Level; L1= Level 1

3.2 GROUND MOTION SELCETION AND SCALING

For this study, 11 Shallow Crustal ground motions from the PEER database were selected, comprising near-field events in the North NF zone within 10km of the rupture surface with forward-directivity characteristics [23]. Ground motions were scaled using "Spectral Matching" to the Ultimate Limit State (0.4T to 1.3T) per New Zealand seismic design code (NZS1170.5) [24]. Damping model selection significantly impacts structural response during post-yielding. For the Isolation system analysis, tangent-stiffness proportional damping was applied to link properties as recommended in [25, 26] to ensure accurate structural displacement measurements. Figure 7 shows scaled spectra for one of the eight case study archetypes.

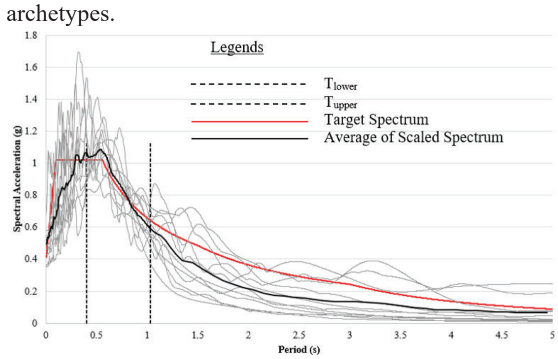

Figure 7: *Scaled acceleration spectra for case stud (h) building archetype.*

4 RESULTS AND DISCUSSION

4.1 RESPONSE SPECTRUM ANALYSIS (RSA)

This study employed Response Spectrum Analysis (RSA) to evaluate the structural performance of the case study archetypes, with subsequent validation through NLTHA. Table 2 presents the seismic performance results for both the base model and case study archetypes as predicted by RSA at the Ultimate Limit State (ULS).

Table 2*: Seismic performance – RSA (ULS)*

Case study archetype	X-direction			Y-direction		
	Fx (kN)	*drift (%)*	*Ductility (μ)*	*Fy (kN)*	*drift (%)*	*Ductility (μ)*
Base case	1163	1.15	2.7	1125	1.26	3.0
a	1152	1.08	3.0	1152	1.09	3.0
b	1122	0.8	3.1	1217	0.91	2.8
c	1016	0.82	3.5	1066	0.88	3.3
d	1122	0.9	3.1	1122	0.91	3.1
e	1093	0.78	3.2	1093	0.79	3.2
f	1066	0.68	3.3	1093	0.72	3.2
g	1093	0.72	3.2	1122	0.75	3.1
h	1152	0.75	3.0	1152	0.74	3.0

Note: Fx = Base shear in X-direction, Fy = Base shear in Y-direction

Response Spectrum Analysis (RSA) was performed to evaluate seismic base shear and drift across different isolation configurations. The RSA base shear was lower than that from the Equivalent Static Method (ESM), and a scale factor was applied as outlined in article 5.2.2.2 (b) in the New Zealand seismic design code (NZS1170.5) [24]. The highest X-direction base shear was observed in

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the base isolation configuration (1163 kN) with ductility of 2.7, while case (c), with isolation at levels 1 and 3, achieved the most significant reduction (1016 kN) and a ductility of 3.5. Most configurations showed reduced demands, except case (b), which recorded a higher Y-direction base shear (1217 kN) than the base case (1125 kN), indicating possible amplification. Overall, Y-direction base shears ranged from 1066 kN to 1217 kN. In the X-direction, RSA results (Figure 8) showed that the base-isolated structure had the highest drift at 1.15% at the base level, followed by case (a) at 1.08%. Case (b) showed moderate drift (0.80% at 6.22 m), and case (e) had intermediate performance (0.78%). Case (f), with isolation at levels 1, 2, and 4, consistently showed lower upper-story drift (0.67%–0.68%). Similarly, in the Y-direction (Figure 9), the base-isolated case again had the highest drift (1.15%), followed by case (a) at 1.09%. Case (b) demonstrated 0.91% drift at 6.22 m, while case (e) recorded 0.79%. Case (f) again had the lowest drifts across upper stories (generally below 0.72%).

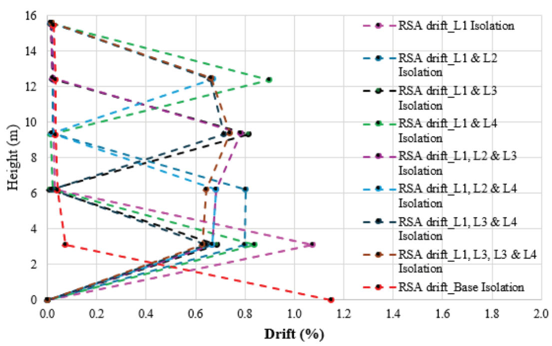

Figure 8: *RSA Inter-storey drift for the 5-Story building archetypes in the X-direction (ULS).*

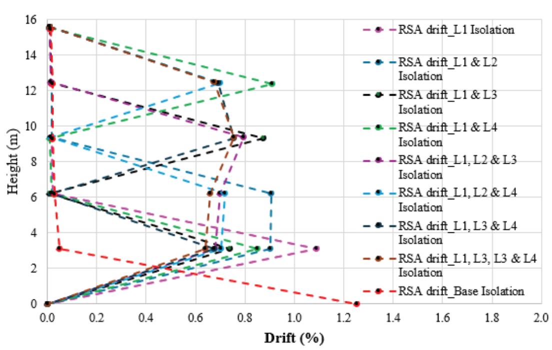

Figure 9: *RSA Inter-storey drift for the 5-Story building archetypes in the Y-direction (ULS).*

4.2 NONLINEAR TIME HISTORY ANALYSIS (NLTHA)

Nonlinear Time History Analysis (NLTHA) was conducted on five-story building archetypes to evaluate their structural response to ground shaking. The study assessed the seismic performance of a proposed connection between CLT walls and CLT floors under a bi-directional design-level earthquake (ULS). NLTHA is an effective method for capturing dynamic effects, including those not accounted for in linear dynamic and nonlinear static analyses. In this study, NLTHA was performed with constant modal damping to ensure consistent energy dissipation across modes and frequencies [26]. The seismic performance of the case study archetypes was evaluated using NLTHA in terms of base shear, inter-story drifts, residual drifts, and floor acceleration. Peak demands were obtained from eleven ground motion records, and their mean values were used to analyze the results.

4.2.1 BASE SHEAR

Nonlinear Time History Analysis (NLTHA) results indicate more significant base shear responses compared to Response Spectrum Analysis (RSA) findings. The base isolation configuration demonstrated the highest base shear values of 1329 kN and 1338 kN in the X and Y directions, respectively. Case studies c-f showed similar results around 970kN in both directions, with ductility (μ) ranging from 3.6 to 3.7. Case study b exhibited the lowest base shear (960kN and 949kN in X and Y directions) with a ductility (μ) of 3.8. Additionally, base shear for Cases a and b was 5% higher than for Cases c-e, resulting in ductility values of 3 versus 3.4 (see Figures 10 and 11). NLTHA-derived base shear estimates were lower than RSA values, confirming RSA as a fast, reliable technique for predicting building seismic performance.

Implementation of the innovative floor-to-wall connection at levels 1, 2, and 4 of a 5-story mass timber building proves beneficial, reducing base shear by approximately 36% (X-direction) and 34% (Y-direction) compared to base isolation systems where base shear amplifies due to timber's inherently lightweight nature (see Figures 10 and 11), aligning with findings from reference [27].

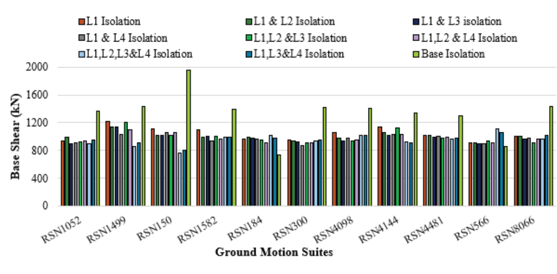

Figure 10: *Seismic base shear for the 5-Story building Archetypes in the X-direction (ULS).*

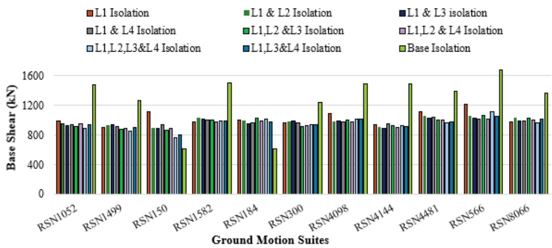

Figure 11: *Seismic base shear for the 5-Story building Archetypes in the Y-direction (ULS).*

4.2.2 INTER-STOREY DRIFT

Nonlinear Time History Analysis (NLTHA) results reveal more pronounced drift behaviours compared to RSA findings. The base-isolated configuration exhibits the highest drift concentration at isolation levels of 2.06% and 2.28% in X and Y directions while maintaining low superstructure drift. Multi-level isolation configurations demonstrate more uniform drift distribution throughout the structure's height. After base isolation, case (a) with isolation implemented at level 1 only shows the highest NLTHA drift values of 0.75% and 0.86% in X and Y directions, indicating potential stress concentration with limited benefits (see Figures 12 and 13).

Case study (b) demonstrates superior drift control in upper stories, suggesting more effective motion control in these regions. Implementing the proposed connection at multiple upper levels significantly reduced displacement demands, exhibiting superior seismic performance as evidenced in the drift response for case studies f-h (see Figures 12 and 13).

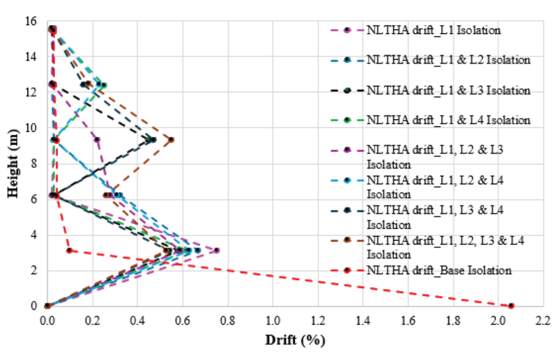

Figure 12: *NLTHA Inter-storey drift for the 5-Story building Archetypes in the X-direction (ULS).*

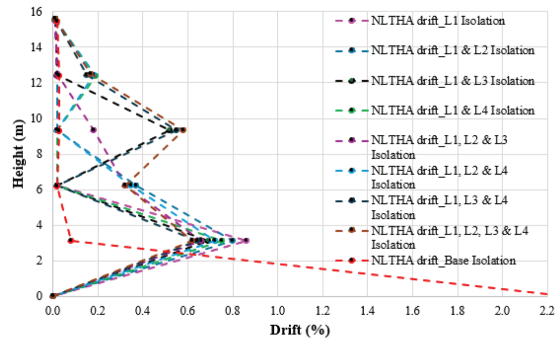

Figure 13: *NLTHA Inter-storey drift for the 5-story building Archetypes in the Y-direction (ULS).*

4.2.3 RESIDUAL DRIFT

Residual drift, which represents the permanent displacements of a structure after an earthquake, is a critical measure of structural integrity and functionality. Structures with residual drifts exceeding 0.5% are more susceptible to aftershock-induced damage, necessitating significant retrofitting for occupant safety [28]. Nonlinear Time History Analysis (NLTHA) results for the eight case study archetypes (a–h) indicated negligible residual displacement, demonstrating superior seismic performance and the ability of the structure to fully self-center after a major earthquake (see Figure 14).

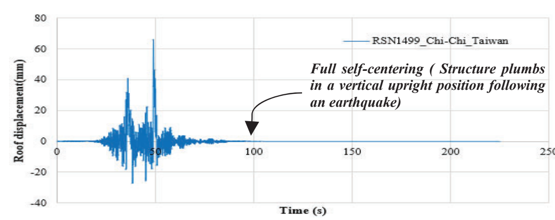

Figure 14: *Residual roof displacement: 5-Story Archetype_ Imperial Valley-Delta (ULS).*

4.2.4 FLOOR ACCELERATION

Floor acceleration refers to the rate at which a flooring system's velocity changes during an earthquake. Controlling floor acceleration in structural design is crucial to minimizing damage to non-structural components and ensuring occupant safety and comfort. The floor acceleration for the studied archetypes is depicted in Figures 15 and 16.

Nonlinear time history analysis (NLTHA) reveals that acceleration patterns differ based on isolation configurations in both X and Y directions. In the X-direction, case study (a) with level 1 (L1) isolation experiences an acceleration of 0.71g at level 1, increasing to 1.26g at level 5. Dual-level isolation presents varying

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trends: case study (b) with isolation at levels 1 and 2 reduces accelerations to 0.61g–0.91g, while case study (d) with isolation at levels 1 and 4 results in a peak of 4.16g at level 4. Notably, case study (f) with isolation at levels 1, 2, and 4 maintains lower accelerations (0.66g–0.77g), whereas base isolation ensures the most uniform performance (0.50g–0.53g).

In the Y-direction, floor accelerations are generally higher. Case study (a) with L1 isolation shows amplification from 1.53g to 1.61g. Case study (b) with isolation at levels 1 and 2 reaches 2.84g at level 2, indicating force concentration. Similarly, case study (d) with isolation at levels 1 and 4 peaks at 4.28g at level 4. Among multi-level configurations, case study (f) maintains accelerations below 1.77g. Base isolation remains the most consistent, with accelerations around 0.50g.

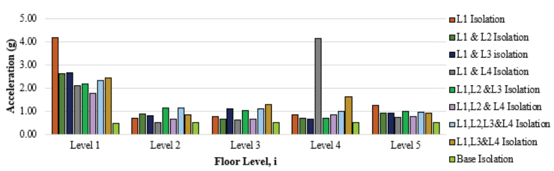

Figure 15: *Floor acceleration for the 5-story building archetypes in the X-direction (ULS).*

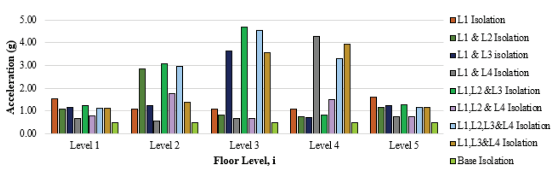

Figure 16: *Floor acceleration for the 5-story building archetypes in the Y-direction (ULS).*

The proposed wall-to-floor connection demonstrates significant potential in enhancing the seismic resilience of platform-type mass timber buildings. Implementing this connection at intermediate floor levels effectively reduces seismic demands, including shear forces and drifts, while minimizing damage to non-structural components. Numerical analyses of eight different archetype configurations indicate that a ductility factor (μ) of 3.0–3.5 can be achieved by strategically placing the proposed connection within a five-story PMMT structure. The ductility factor, evaluated using response spectrum analysis (RSA) and validated through nonlinear time history analysis (NLTHA), confirms that RSA is a reliable linear dynamic analysis approach, providing an accurate and conservative basis for design considerations. However, the study also highlights a limitation of base isolation in mass timber buildings, where the inherently low structural weight reduces the effectiveness of the isolation system, leading to elevated base shear forces.

Inter-story drift results from RSA were maintained below 1%, complying with code requirements. The highest drifts were observed in the base isolation configuration, followed by case (a), where isolation was applied only at level 1. Conversely, case (f), incorporating isolation at multiple levels, recorded the lowest drifts (0.55% in the X-direction and 0.6% in the Y-direction). These findings suggest that multi-level isolation planes effectively reduce inter-story drifts, whereas base isolation alone can lead to excessive drifts. Such large deformations necessitate specialized design solutions for moat walls, expansion joints, and building services, contributing to higher construction costs and increased land requirements.

Additionally, the proposed connection exhibited self-centering behavior, significantly minimizing residual displacements after seismic events. This characteristic enhances post-earthquake recovery and reduces maintenance costs, aligning with seismic-resilient design principles. NLTHA results further indicate that story accelerations were highest in case (a), while base isolation provided the most uniform acceleration response. Case (f), where the proposed connections were implemented at levels 1, 3, and 4, demonstrated an optimal balance of acceleration reduction and drift control. Overall, the findings underscore the importance of robust inter-story isolation connections in advancing the seismic resilience of mass timber buildings, offering a promising solution for next-generation seismic-resistant structures.

5 CONCLUSIONS

This study shows the benefits of implementing an innovative connection between CLT wall and CLT floor panels in platform-type construction. Unlike conventional connections that experience significant strength and stiffness degradation under cyclic loading, this resilient connection potentially eliminates damage in wall-to-floor connections while providing robust seismic performance and resilience for next-generation mass timber construction. The proposed connection offers an ideal solution for modular construction, enabling stacking of modular units to form larger permanent buildings. Seismic demands can be significantly reduced through this novel connection, as demonstrated analytically. While inherently low mass in timber structures limits base isolation effectiveness (reduced period shift due to low mass restricts damping in the system, rendering it ineffective for lowering shear demands).

The findings of this study revealed that a ductility factor (μ) ranging from 3.0 to 3.5 can be easily achieved in a five-story mass timber building through implementing the proposed connection at multiple levels between CLT walls and floor panels. Notably, optimum locations for implementation are at levels 1, 2, and 4, exhibiting ideal seismic performance regarding base shear, inter-story drifts, residual drifts, and floor acceleration at design level earthquake (ULS).Moreover, the five-story case study building with the proposed connection in X and Y directions yielded zero permanent displacement, displaying full self-centering capability at design-level earthquake (ULS). Structures using this connection will not require significant retrofit following design-level earthquakes and resist aftershock damage. Additionally, reductions in lateral displacement and floor acceleration will reduce damage to non-structural components. Base shear demand reduction redirects lower design forces to lateral load-resisting system sub-components and foundation, reducing overall project cost. The connection provides acceptable energy dissipation, ductility, and self-centering capability as a resilient solution for prefabricated modular mass timber construction.

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