Seismic performance of prefabricated modular mass timber structures with inter-story isolation

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ABSTRACT

Mass Timber products such as Cross Laminated Timber (CLT) have emerged as a high-performance construction material inhibiting high in-plane and out-of-plane stiffness, enabling them to be used as prefabricated wall and floor panels, aligning with modular construction approach. Prefabricated Modular Mass Timber (MMT) construction provides an alternative to traditional on-site light timber construction. MMT buildings consist of prefabricated volumetric modules assembled on-site to form a larger, permanent structure. Because the prefabricated modules are constructed off-site in a controlled environment, they offer consistent quality, resource efficiency, and a sustainable building solution. However, numerous research and experimental tests have shown that conventional connections used to facilitate the assembly of prefabricated mass timber modules do not meet the damage avoidance and sustainability criteria of mass timber design.

This paper proposes an innovative Resilient Floor Isolation System (RFIS) for MMT construction. The proposed systems effectiveness and advantages have been investigated and illustrated in this paper. Numerical modelling of MMT with story isolation at intermediate levels was developed in ETABS. The seismic performance of MMT with RFIS at subsequent building levels was evaluated using static pushover and Non-Linear Time History Analysis (NLTHA) and compared with a conventional mass timber building designed using Displacement Based Design (DBD). Data from time history analysis revealed that introducing inter-story isolation at intermediate levels of a building reduces the force demands on prefabricated MMT, thus leading to improved seismic response. The findings of this research exemplify that the proposed concept can be a potential candidate for low-rise mass timber buildings made of prefabricated MMT.

1 INTRODUCTION

Timber as a construction material has gained global interest due to its positive environmental characteristics and aesthetic features (Kotradyova et al., 2019). The construction of residential and high-rise buildings with wood, in particular, will not be efficient without prefabrication in modern construction practice. Engineered wood products such as CLT have become an ideal mass timber element recognized for prefabricated Modular Mass Timber (MMT) construction. The cross-lamination in CLT imparts high in-plane and out-of-plane stiffness, enabling the panels to be used as wall and floor configurations (Abed et al., 2022; Karacabeyli, 2019).

The modules comprising CLT wall and floor panels are fabricated off-site as a volumetric module, offering consistent quality, efficient resource utilization and contributing to a sustainable solution for the construction industry (Lacey et al., 2018; Ramaji & Memari, 2016). In practice, MMTs are connected using conventional connections such as screws, rivets, metal fasteners, and bolts in a platform style (Chen & Popovski, 2020) to resist the induced earthquake demands. These connections are prone to experience significant strength and stiffness degradation, making them vulnerable to aftershocks. Thus, to achieve the objective of seismic design, i.e., life safety, immediate occupancy, and collapse prevention, an innovative wall-to-floor connection is proposed for MMT buildings that can potentially address the current inadequacies of conventional connections.

1.1 Limitations in the current modular mass timber connections

Extensive research has been conducted in the past two decades to evaluate the seismic performance of Modular Mass Timber structures. The most comprehensive study on CLT modules assembled in a platform style was conducted within the SOFIE project (Ceccotti, 2008; Ceccotti et al., 2013). A series of shake table tests on a full-scale three-story and a seven-story CLT building built in a modular nature revealed that CLT modular structures built in a platform style construction are relatively stiff, and the energy dissipation in the system is provided by the connection between the prefabricated CLT panels. Some level of damages in the metal hold-downs were observed during the test with the CLT prefabricated modular mass timber building built in a platform-style construction, demonstrating an acceptable level of seismic performance at simulated peak ground acceleration of 0.82g. However, the stiff nature of the building resulted in a high floor acceleration of approximately 3.8g at the upper level. Such high acceleration could lead to serious injuries and fatalities.

Popovski et al. (2016) experimentally investigated the seismic performance of a two-story Mass Timber building in which two CLT modules were stacked onto each other in a platform layout (see Figure 1a). Test results revealed that CLT wall panels remained intact, and all the damages were concentrated on the CLT hold-down connections. It was also concluded that conventional connections connecting the CLT modules in a platform layout could achieve ductility of 3 (Popovski & Gavric, 2016). In a similar study, van de Lindt et al. experimentally investigated the seismic performance of a full-scale two-story modular CLT house through a series of shake table tests (van de Lindt et al., 2019). This study concluded that low aspect-ratio shear walls are susceptible to sliding, resulting in wall hold-downs failing in shear, thus significantly reducing the strength and stiffness of the conventional connections. The permanent damages observed in the conventional connections during the test are shown in Figure 1.


(a) (b) (c) (d)

Figure 1. Failure mechanism in bracket connections of a two-story CLT house: (a) Full-scale modular CLT house (b) wood failure due to nail fatigue resulting from sliding of the panel, (c) nail withdrawal and yielding due to bi-directional loading, and (d) partial withdrawal of nails from off-the-shelf hold-downs (Popovski & Gavric, 2016).

To address the shortcomings of strength and stiffness degradation in modular mass timber connections. Chen et al. (2020) analytically investigated the seismic performance of the Floor Isolated Re-centring Modular Construction System (FIRMOC) for CLT platform buildings. The FIRMOC system is a combination of a rocking and energy dissipation mechanism. The rocking mechanism provides re-centering through Post-Tension (PT) cables and energy dissipation through mild steel yielding while energy-dissipating devices can be implemented between modules. The results from non-linear time history analysis complying with principles set in NBCC 2015 demonstrated that approximately 50% of the seismic-induced forces can be reduced by using the proposed FIRMOC system. Additionally, the maximum inter-story drift of 0.4% was recorded, with a significant reduction in floor acceleration observed by employing the proposed lateral load-resisting system in a modular CLT structure (Chen et al., 2020).

Numerical studies with inter-story isolation have also shown that introducing floor isolation at intermediate building height through isolation devices can significantly reduce seismic demands (Chang et al., 2010; Murakami et al., 2000; Zhou et al., 2004). Analytical studies have also indicated that implementing inter-story isolation at higher levels notably reduces force demands compared to lower levels. However, relocating the isolation layer at the upper levels resulted in reduced effectiveness, offering a limited reduction in base displacements (Ryan & Earl, 2010). Consequently, the insight from Chang et al., 2010; Murakami et al., 2000 and Zhou et al., 2004 served as the foundation for developing four case study building archetypes incorporating the innovative wall-to-floor connection for prefabricated MMT, deployed at respective floor levels of the 5-story modular mass timber building, as depicted in Figure 3.

2 THE PROPOSED INTER-STORY ISOLATION CONCEPT

Inter-story isolation at predefined floor levels eliminates the need for expensive foundations, including seismic gaps (moat), and reduces the inter-story shear forces (Bolvardi et al., 2018). The proposed concept employs a proprietary material that is connected to the CLT floor panel and the CLT wall individually, creating an interface to allow for a sliding mechanism through friction generated between the low friction material installed at predefined locations underneath the CLT floor and on top of the CLT wall panel as shown in Figure 2. The friction coefficient for the proprietary material is approximately 25%, with a compressive strength of 26MPa. During an earthquake, the CLT floors slide relative to the walls, dissipating the energy through friction between the proprietary materials connected to both components. The sliding between the low-friction material dissipates the earthquake-induced energy while maintaining stiffness. The proposed damping device resembling a friction isolator is similar to Loo et al., (2014), with zero reduction in strength and stiffness.

Resilient Slip Friction Joint (RSFJ) facilitates the system's centering and partial energy dissipation. In the RSFJ's, energy is absorbed through frictional sliding of the plates coated with a proprietary material. RSFJs offer energy dissipation, self-centering, and increased force/displacement capacity through a secondary fuse activation during earthquakes. This allows for 1.75 to 2 times the displacement capacity, with a reserve force capacity of 1.35 beyond design displacement (Hashemi & Quenneville, 2020; Hashemi, Zarnani, Darani, et al., 2018; Hashemi, Zarnani, Masoudnia, et al., 2018; Hashemi et al., 2020a, 2020b).

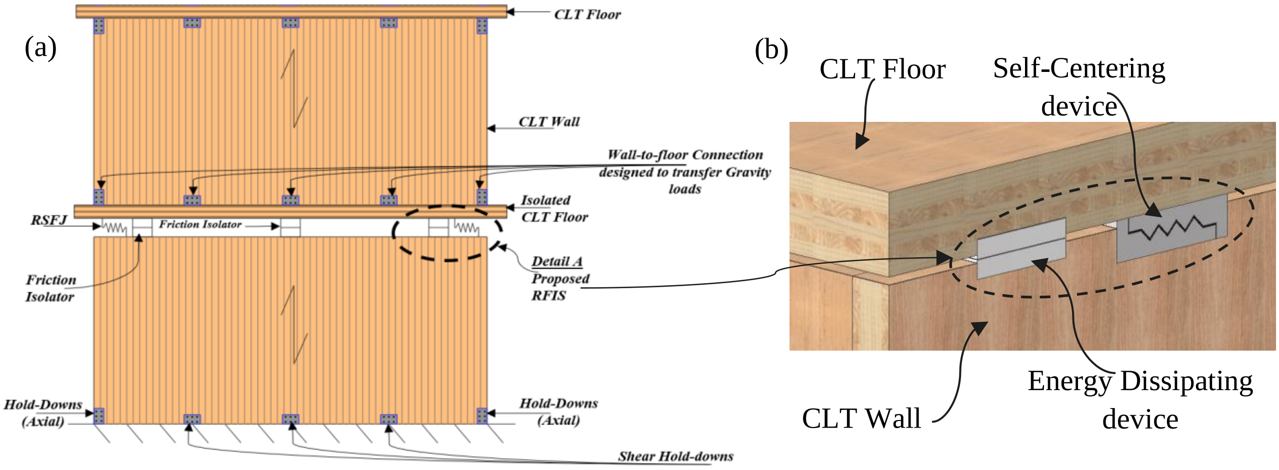


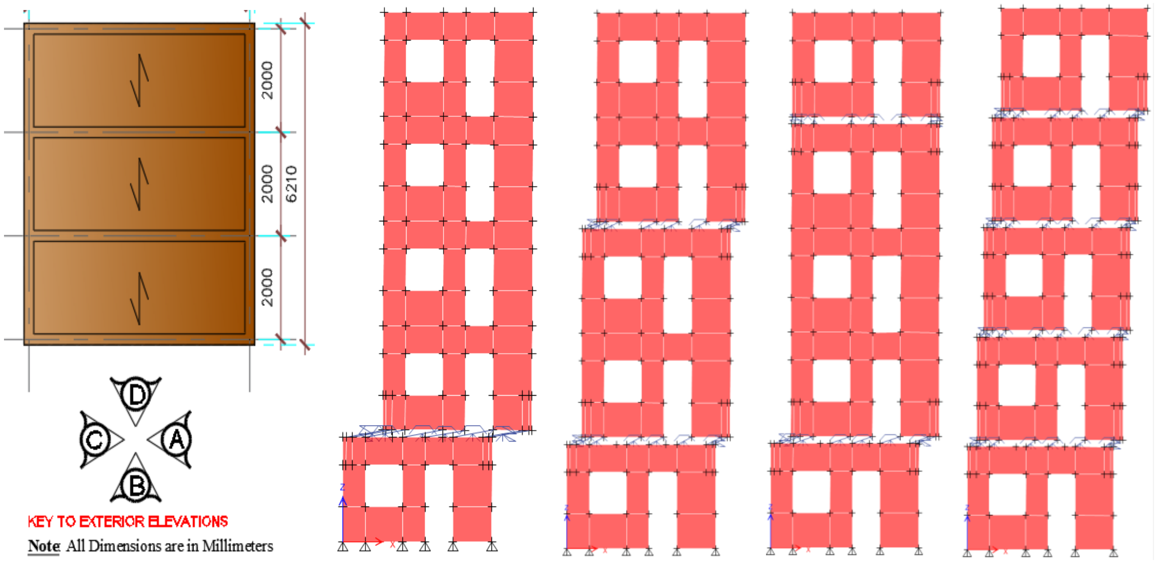
Figure 2. Proposed RFIS: (a) 2D schematic, and (b) Connection between CLT floor and wall

The RFIS is prefabricated off-site, with provisions for connecting it to the CLT wall and floor panel. The RFIS, which consists of an energy-dissipating device and a mechanism to provide the restoring force with some level of damping in the system, is directly connected in the pockets created in the prefabricated CLT wall and floor panel as shown in Figure 2 (b). The friction pads provide the necessary energy dissipation in the system is connected to the wall and floor using off-the-shelf countersunk screws. The provisions for connecting the self-centering devices to the CLT panels are ready-made in the devices and is directly bolted to the CLT wall, and the Isolating Floor positioned above the wall. A swivel is employed in the self-centering mechanism to accommodate deformation compatibility and enable out-of-plane rotation in the orthogonal direction when the floor isolates unidirectionally due to in-plane loading.

3 METHODOLOGY

ETABS software was used to develop 3D numerical models of the case study archetypes, aimed at evaluating the seismic performance of the proposed RFIS concept in a 5-story MMT building comprising CLT floor and wall panels resisting both gravity and lateral loads. The in-plan dimensions of the case study structures were adopted from (Popovski & Gavric, 2016), having an in-plan dimensions of 6.0m x 4.8m. However, the building height was adjusted to 3m to represent a real residential building, with subsequent floors, including the first floor, measuring 3m in height. The floor panels, including the walls at levels 1 and 2, consist of a 5-layer CLT panel composed of Machine Stress Graded sawn timber with the modulus of elasticity (E) of 8GPa (MSG8) in both longitudinal and transverse lamination while levels 3, 4, and 5 walls, including the roof utilizes a 3-layer CLT panel composed of Machine Stress-Graded sawn timber with modulus of elasticity (E) of 8GPa (MSG8) in longitudinal direction and 6GPa (MSG6) in the transverse direction. For simplicity and for the numerical model to converge easily. The staircase openings in the floors were ignored.

The seismic weight of level 1, 2, 3, 4, and 5 is 168kN, 152kN, 135kN, 135kN, and 84kN, respectively. Seismic forces were determined using Displacement-Based Design (DBD) for a soil-type D with the building assumed to be located in Wellington, New Zealand. The established non-linear pushover was used as the starting point to check the non-linear behaviour of the links, and NLTHA was used to verify the effectiveness of the proposed system in capturing suitable variabilities for this analytical study. The hysteretic behaviour of the Friction Isolator and RSFJ is numerically represented by the “Friction Isolator” and “Damper - Friction spring” link element in “SAP2000” or “ETABS”. Figure 3 illustrates the in-plan dimensions and exterior elevations under consideration for this study.



(a) *(b)* *(c)* *(d)* *(e)*

Figure 3. Schematic of the case study building archetypes with RFIS implemented at level i: (a) In-Plan view (b) Isolation at Level 1, (c) Isolation at Level 1 and Level 3, (d) Isolation at Level 1 and Level 4, and (e) Isolation at Level 1, Level 2, Level 3, and Level 4.

Table 1. Summary of the case study archetype specifications

Case Study Building Archetype	Implementation of Floor Isolation at Level, i	Total number of RSFJs	Number of Friction Isolators at Level, i
a	Level 1	8	30
b	Level 1 and Level 3	16	60
c	Level 1 and Level 4	16	60
d	Level 1, 2,3, and Level 4	32	120

Note: 8 RSFJ links and 30 Friction Isolator links are simulated at each isolation level

3.1 Selection of ground motion records and scaling

A suite of 11 ground motions (total of 22 horizontal components) was used to evaluate the seismic performance of the case study building archetypes (Oyarzo-Vera et al., 2012). The selected ground motions reflect the subset of zone North NF records for the north island of New Zealand (Oyarzo-Vera et al., 2012). The selected ground motion records were scaled using the spectral matching method to the Ultimate Limit State (ULS) between 0.4T and 1.3T, as suggested by (NZS1170.5:, 2004). Non-Linear Time History Analysis (Direct Integration) was then performed on the four case study-building archetypes to evaluate the effectiveness of the proposed RFIS with prefabricated MMTs. The system was then compared for base shear, inter-story drift, residual drifts, and floor acceleration.

4 RESULTS AND DISCUSSION

4.1 Performance of the proposed floor isolation system

A five-story prefabricated modular mass timber comprising of conventional connection is designed to achieve a ductility factor of 2.5, yielding a base shear of 304kN limited to a maximum drift of 1.5% drift. This building is used to evaluate the effectiveness of implementing seismic isolation at subsequent floor levels. Ductility in the similar range was also reported in the tested building with conventional connections (Popovski & Gavric, 2016). NLTHA was performed on the case study archetypes to evaluate the seismic performance of the system under design-level earthquakes. For each case study archetype, the mean of the eleven records is used to assess the seismic performance. The maximum demands for individual records were also plotted, as shown in Figures 4-7. The influence of vertical acceleration was not considered for this analysis.

The average estimated base shear from NLTHA for the case study building archetype (a) with RFIS implemented at level 1 was approximately 257kN in the x-direction and 264kN in the y-direction, yielding an equivalent ductility factor (μ) of 3.1. On the other hand, the average estimated base shear from NLTHA case study building archetypes (b), (c), and (d) were similar in the range of 275kN in both x and y-direction, yielding an equivalent ductility factor (μ) of 3.0. A reduction of approximately 10-15% base shear was observed in the building archetype with RFIS implemented at level 1 compared to the archetype incorporating RFIS at all levels. It is evident that implementing the proposed RFIS at level 1 yields the lowest base shear and requires fewer devices (refer to Figures 4 and 5), offering a resilient solution for prefabricated MMT construction. This helps to reduce the cost of conventional connections that are vulnerable to damage in case of an event.

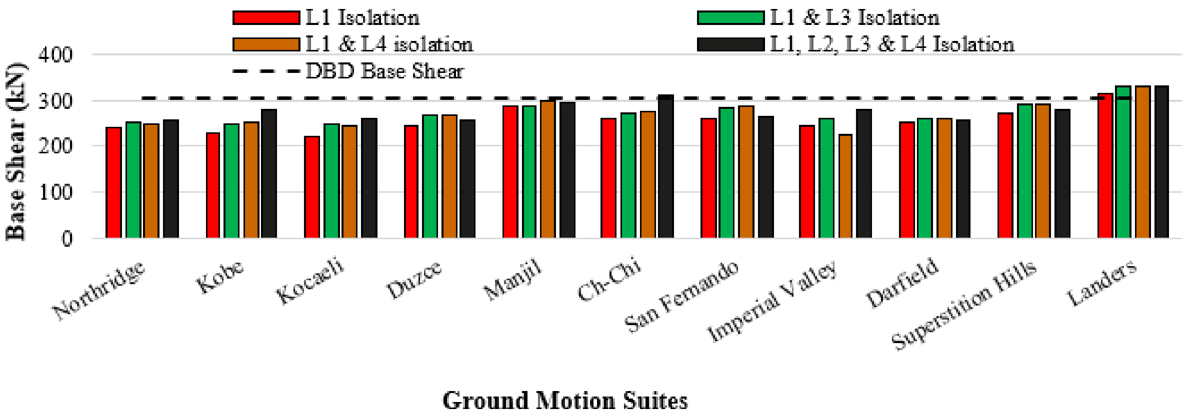


Figure 4. Comparison of ULS Base Shear in X-Direction: 5-Story Archetype

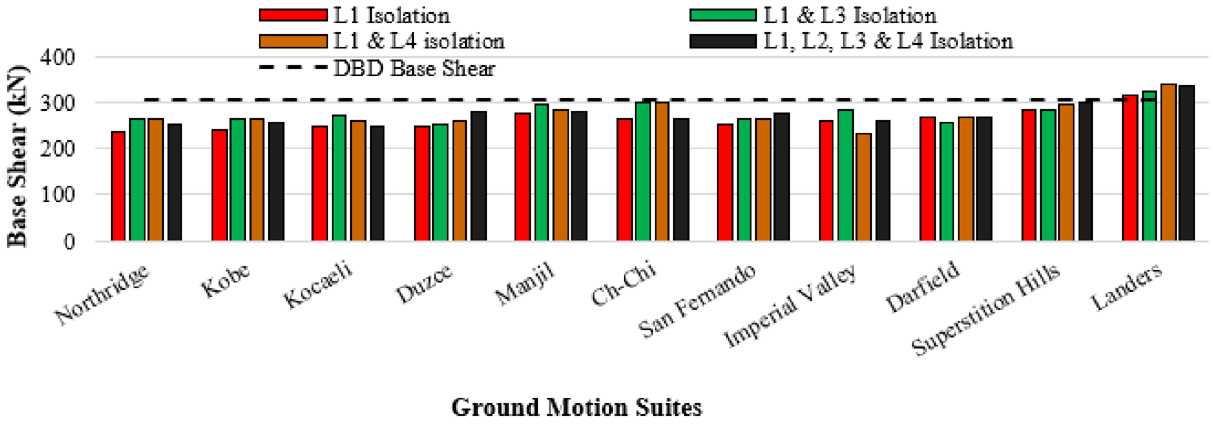


Figure 5. Comparison of ULS Base Shear in Y-Direction: 5-Story Archetype

The average estimated inter-story drift from NLTHA for the case study archetype (d), with RFIS implemented at all levels except for the roof was approximately 1.4% in both x and y directions. On the contrary, the average estimated inter-story drift from NLTHA case study building archetypes (a), (b), and (c) were similar in the range of 1.0% and 0.9% in the x-direction and y-direction, respectively. In comparison, approximately 29% higher drifts were observed in case study (d). Based on the NLTHA results, there were limited benefits observed in terms of inter-story drifts when integrating the proposed RFIS at all levels of the building (case (d)). It was also noticed that implementing the proposed inter-story isolation at every floor level increased the displacement demand, resulting in high drifts (see Figures 6 and 7).

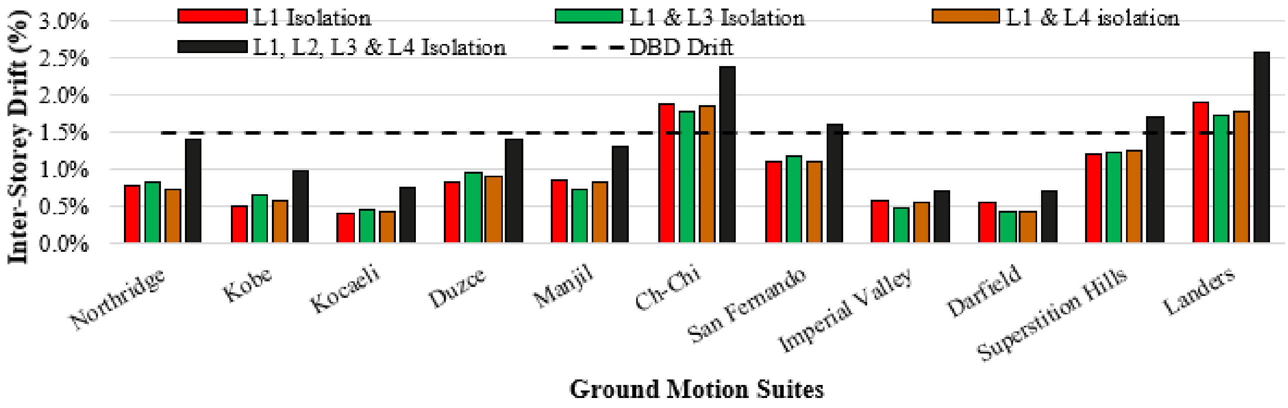


Figure 6. Comparison of ULS inter-story drift in X-Direction: 5-Story Archetype

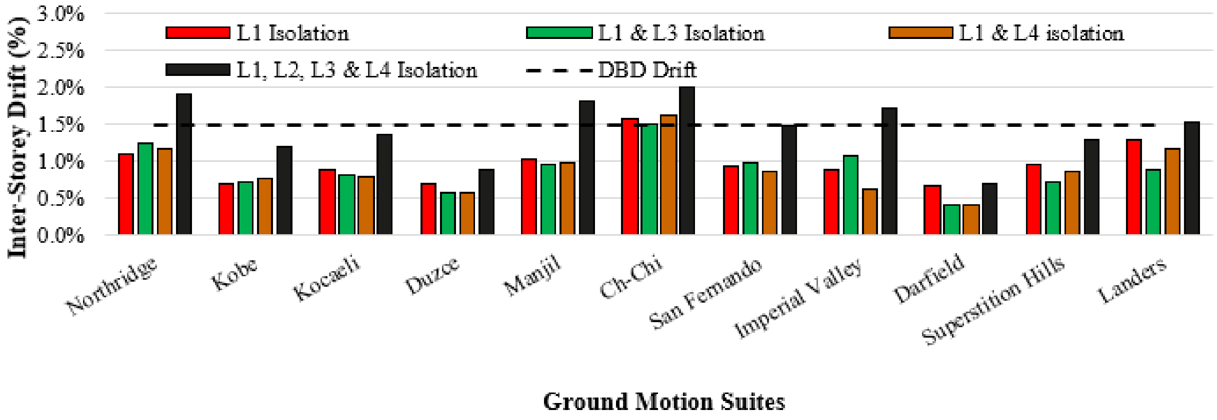


Figure 7. Comparison of ULS inter-story drift in Y-Direction: 5-Story Archetype

Additionally, the system with the proposed inter-story isolation exhibited self-centering characteristics with negligible permanent displacements. Figure 8 illustrates the self-centering behaviour of the 5-story prefabricated MMT building when subjected to a design-level earthquake ground motion (RSN169-Imperial Valley- Delta).

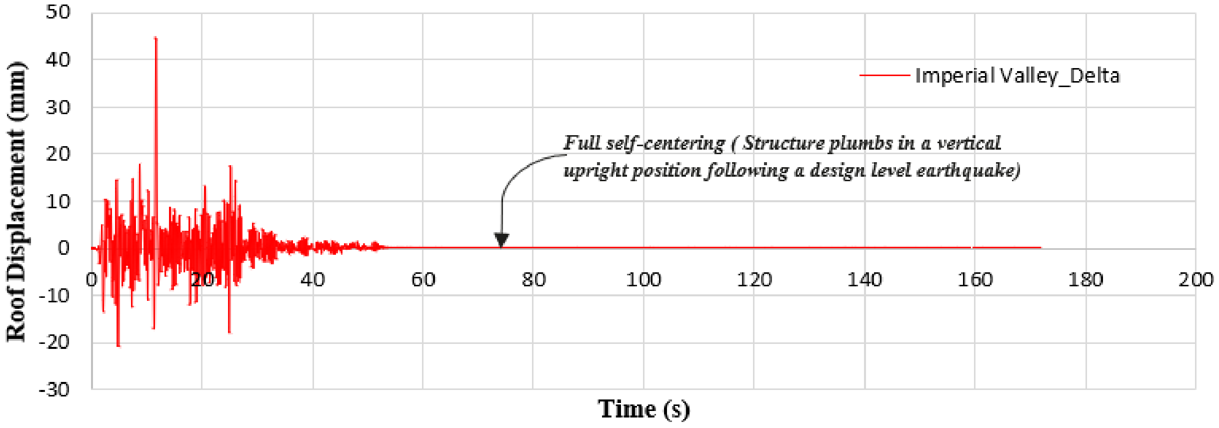


Figure 8. Residual displacement (ULS): 5-Story Archetype_ Imperial Valley-Delta

Moreover, ensuring the safety of human life is the utmost priority in any structure. High floor acceleration can lead to serious injuries or potential fatalities among building occupants. Minimizing floor acceleration significantly reduces the risk of harm to individuals during seismic events. Figure 9 illustrates the floor accelerations for x and y directions recorded in the respective case study building archetypes.

Results from NLTHA revealed that implementing RFIS at the bottom level only, similar to case (a) of this analytical study, exhibited higher floor acceleration of approximately 0.61g in both x and y directions at the uppermost level. On the other hand, a significant reduction in floor acceleration was observed at mid-height of the building, capped at 0.39g and 0.43g in the x and y directions, respectively. It was also noted that implementing floor isolation at level 1 and at level 3 of the 5-story building archetype resulted in the lowest floor acceleration, measuring around 0.53g and 0.55g in the x and y directions, respectively, at the topmost level, while keeping floor acceleration nearly constant at all other levels. This shows the effectiveness of implementing the proposed RFIS at subsequent building levels to filter the earthquake-induced energy. Figure 13 shows the story acceleration for the respective case study archetypes.

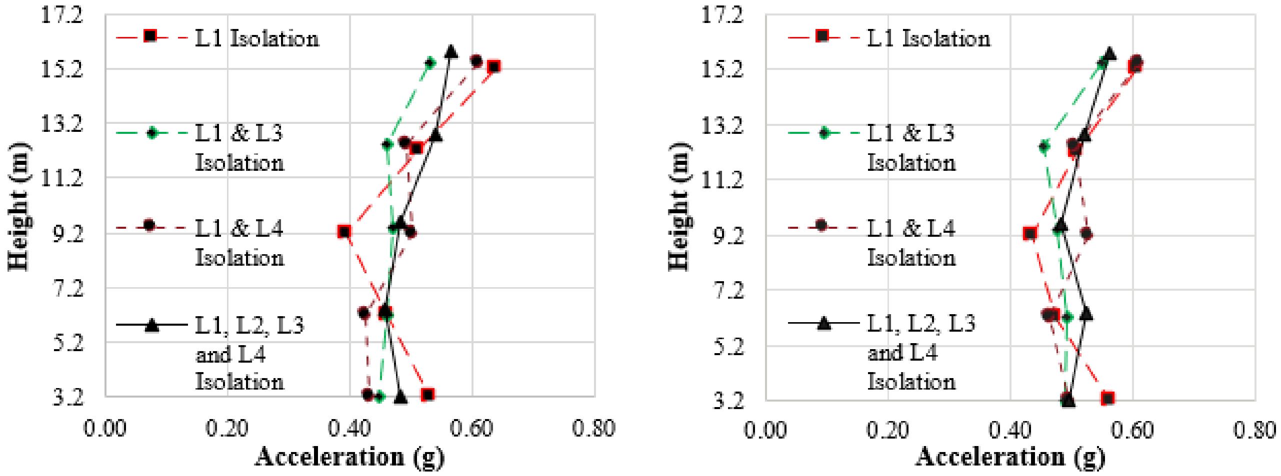


Figure 9. Floor Acceleration: (a) X-Direction and (b) Y-Direction

The maximum rooftop displacements of 82mm and 64mm were observed in the x and y direction in the case study building archetype with RFIS implemented at all levels (case (d)). On the other hand, the lowest rooftop displacement was observed in case study (a), capped at 61mm and 51mm in the x and y directions, respectively.

5 CONCLUSION

The effectiveness of implementing the novel inter-story isolation connection (RFIS) for wall-to-floor assembly is presented in this paper and can be used as a substitute for the conventional connections to mitigate the permanent damages resulting in significant strength and stiffness degradation. This study shows that implementing RFIS at subsequent floor levels of a five-story prefabricated MMT building or similar structures could yield a ductility of three (3) or higher. Moreover, findings from NLTHA revealed that implementing RFIS at multiple levels, including the upper level, significantly reduces the force demands in the structure but shows a limited reduction in displacements. Consequently, despite integrating a large quantity of devices, the system's effectiveness is reduced. Conversely, incorporating the proposed RFIS at level one of the five-story building archetype displayed maximum benefits out of the four archetypes considered for this numerical study showing significant reduction in the base shear, drifts, and floor acceleration while utilizing the fewest number of devices. Consequently, this arrangement demonstrated considerable cost savings in terms of device usage.

In addition to reducing the force and displacement demands, the five-story prefabricated MMT buildings with RFIS at subsequent stories exhibited zero residual drifts, displaying a self-centering behaviour under design-level earthquake with an acceptable level of ductility and damping. The self-centring capability of the proposed inter-story connection in prefabricated MMT buildings requires zero maintenance following an earthquake. Overall, the implementation of RFIS displayed superior seismic performance in terms of inter-story drift, base shear, residual drift, and floor acceleration under design level (ULS) earthquake. Thus, reducing the force demands on the sub-structure and minimizing the damage to structural and non-structural building components. The proposed RFIS can fulfill the crucial requirements of a lateral load-resisting system, including self-centering, ductility, and damping.

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