
A System-Level Evaluation of the Seismic Performance of Different Drywall Partitions in Shake-Table Experiments

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ABSTRACT

Experience from recent earthquakes indicates that non-structural elements (NSEs) contribute significantly to seismic financial losses and functional disruption. Among various types of NSEs, drywall partition walls are of particular importance, as they are not only widely used in buildings but also vulnerable to earthquake shaking induced damage. In practice, partition walls are connected to other NSEs (ceilings, other partition walls) and structural elements, thereby interacting with earthquakes. These interactions can significantly influence the seismic performance of partition walls. For this purpose, a research project was initiated in which partition walls were installed and tested in an enclosed room configuration as part of a wider shake-table test of a five-story building. Four rooms were constructed with varying corner joint and connection details, each including perimeter-fixed plasterboard concealed ceilings. The building was subjected to different levels of shaking on a shake table, and the seismic performance of the partition walls in each room was assessed. This paper investigates the effect of different corner joint and connection details on the seismic behavior, damage, and failure modes of partition walls. These findings can contribute to making more informed decisions in the seismic design and construction of partition walls, thereby reducing seismic financial losses caused by their performance in the future.

1 INTRODUCTION

Current prescriptive seismic design codes are based on a design philosophy that aims to limit the collapse probability of buildings to a target level that addresses the life safety of building occupants in a severe earthquake. Recent earthquakes have demonstrated the effectiveness of the current seismic design approach in reducing earthquake-induced casualties to an acceptable level. However, these earthquakes have shown that buildings designed based on this approach can suffer significant financial losses and prolonged loss of function (Marquis et al., 2017). The seismic financial losses and functional recovery time are both directly related to the extent of damage that different elements of the building sustain during earthquakes. Among these different elements, non-structural elements (NSEs) contribute significantly to the seismic financial losses of buildings (Taghavi & Miranda, 2003; Dhakal et al., 2016). Damage to NSE partition walls can make a significant contribution to earthquake-induced economic losses and hinder the post-earthquake functionality of buildings during moderate earthquakes (Arifin et al., 2021). This is because they are widely used in various building types, including multi-story commercial, hospital, and residential buildings, and are vulnerable to damage in minor-to-moderate earthquakes. Specifically, partition walls have been shown to sustain damage even at low earthquake demands (e.g., at inter-story drifts as low as 0.3%), as observed in post-earthquake reconnaissance and previous experimental studies (Restrepo & Bersofsky, 2011). Furthermore, many other types of NSEs, such as finishes, doors, furniture, plumbing fixtures, and mechanical and electrical systems, are attached to or embedded in partition walls. Consequently, damage to partition walls can lead to damage to many NSEs, which not only account for a significant portion of the total construction costs of buildings but also play important roles in building operation.

Recent experimental studies (Retamales et al., 2013; Pali et al., 2018; Fiorino et al., 2019; Araya-Letelier et al., 2019; Menegon et al., 2023b) have indicated that different construction details used to connect various components of partition walls can significantly affect the type and extent of damage these walls sustain under earthquake demands. Similarly, the connection of partition wall assemblies to the surrounding structural and non-structural elements is equally important. To investigate the effect of various partition wall connection detailing on partition wall damage, testing was undertaken on four partition wall subassemblies (in the form of rooms). Each room consisted of four partition walls with varied detailing, including:

- presence of door openings;
- low-damage and conventional connection details (to the slab and at wall returns);
- single- versus double-lined plasterboard linings;
- full-height versus partial-height plasterboard linings; and
- variable base and head track connection details.

The rooms were constructed and installed on the second and third floors of a full-scale five-story building. Their seismic performance was then investigated by subjecting the building to gradually increasing shaking levels using the National Centre for Research on Earthquake Engineering (NCREE, Taiwan) shake table facility. In this paper, preliminary observations of damage patterns and response mechanisms of the partition walls at different levels of seismic intensity are discussed.

2 EXPERIMENTAL PROGRAM

The test structure, shown in Figure 1, was a five-story building with a 5.4 m by 5.4 m square plan and one bay in each direction. The total height of the building was 12.6 m, and the floor heights, measured from the top of one slab to the top of the slab above, were 2.6 m for the first floor and 2.5 m for the remaining floors. Partition wall–ceiling systems were constructed and installed on the second and third floors of the building, as shown in Figure 1(b). The building was then subjected to 3D earthquake excitations at various intensity levels using a high-performance triaxial shake table located at the NCREE Laboratory in Tainan, Taiwan. The test program was conducted in three phases. In phase 1, the building was tested without buckling restrained braces (BRBs) under lower levels of shaking, as shown in Figure 1(a). In phase 2, BRBs were

installed as shown in Figure 1(c), and the building was tested under stronger levels of shaking. In phase 3, the BRBs were removed, and the building was again subjected to strong levels of shaking.

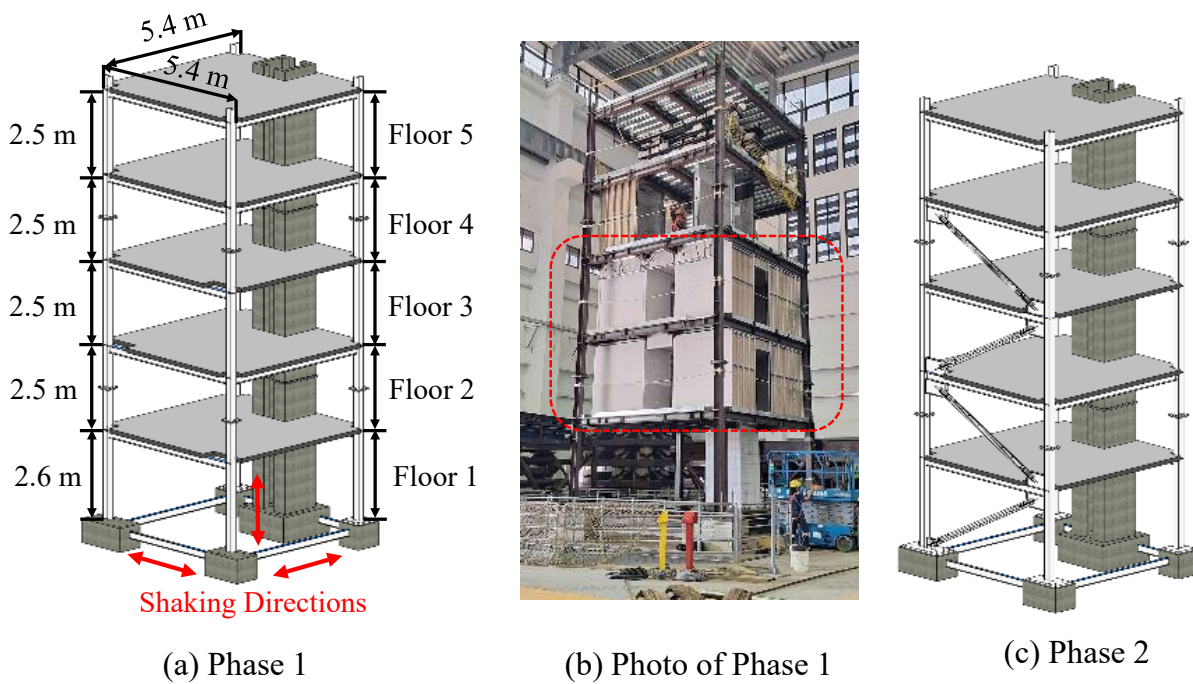


Figure 1: Configuration of the test specimen: (a) bare structure in Phase 1; (b) Phase 1 after installation of the partition wall–ceiling systems; and (c) bare structure in Phase 2.

Table 1: Test matrix with measured peak ground parameters. X direction refers to the NS direction (South positive), Z refers to the EW direction (East positive), and Y refers to the vertical direction (Vertical positive).

Run	Record	Direction ^a	Configuration	NS (X)			EW (Z)		
				PGA (g)	PGV (cm/s)	PGD (mm)	PGA (g)	PGV (cm/s)	PGD (mm)
-	Table Limits	-	-	±1.4	±200	±1000	±1.4	±200	±1000
1	El Centro 1940	X	Unbraced	-	-	-	0.08	10	36
2	El Centro 1940	Z	Unbraced	0.16	13	31	-	-	-
3	El Centro 1940	X+Z	Unbraced	0.15	13	33	0.09	10	36
4	El Centro 1940	X+Y+Z	Unbraced	0.16	13	32	0.09	10	35
5	El Centro 1940	X	Unbraced	-	-	-	0.17	20	70
6	El Centro 1940	Z	Unbraced	0.34	25	63	-	-	-
7	El Centro 1940	X+Z	Unbraced	0.34	26	68	0.19	20	69
8	El Centro 1940	X+Y+Z	Unbraced	0.36	26	63	0.17	20	74
9	El Centro 1940	X	Braced	-	-	-	0.07	9	31
10	El Centro 1940	Z	Braced	0.15	14	24	-	-	-
11	El Centro 1940	X+Z	Braced	0.15	14	25	0.09	9	30
12	El Centro 1940	X+Y+Z	Braced	0.15	15	29	0.09	9	32
13	El Centro 1940	X	Braced	-	-	-	0.17	18	65
14	El Centro 1940	Z	Braced	0.31	28	49	-	-	-
15	El Centro 1940	X+Z	Braced	0.31	30	58	0.18	19	68
16	El Centro 1940	X+Y+Z	Braced	0.32	30	59	0.20	20	70
17	El Centro 1940	X+Z	Braced	0.31	30	55	0.19	19	70
18	El Centro 1940	X+Y+Z	Braced	0.31	30	54	0.20	19	60
19	El Centro 1940	X+Y+Z	Braced	0.44	44	77	0.31	28	98
20	El Centro 1940	X+Z	Braced	0.60	60	109	0.41	39	125
21	El Centro 1940	X+Y+Z	Braced	0.59	62	101	0.44	40	136
22	El Centro 1940	X+Z	Braced	0.73	74	128	0.52	52	166
23	El Centro 1940 ^b	X+Z	Braced	0.55	51	155	0.70	70	152
24	El Centro 1940 ^b	X+Z	Braced	0.66	61	203	0.84	84	176

^a X: NS direction (+X is south); Z: EW direction (+Z is east); Y: vertical direction (+Y is up)

^b NS and EW components swapped

The ground motion used was the 1940 El Centro, California, earthquake record, which was scaled to be consistent with the acceleration spectrum used for the building's design. In this study, the response of the partition wall subassemblies is discussed for phases 1 and 2 only. The excitation history for these two phases, including peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) intensities are summarized in Table 1.

3 OUTLINE OF THE PARTITION WALL-CEILING SYSTEM

Steel stud partition wall–ceiling systems were implemented in the form of two symmetrical rooms on each floor, located on second and third floors, with the typical plan layout illustrated in Figure 2 (a). Further details regarding the construction of the partition wall systems are provided in the following sections.

3.1 Partition wall systems

Each room comprised five plasterboard-lined walls: two single-lined walls, two double-lined walls, and one direct-fix wall that is fixed to the concrete core wall. The typical elevation views and dimensions of these walls are illustrated in Figure 2 (b). Typical connection details between the top and bottom of the partition wall and the concrete floor slabs are illustrated in Figure 3. In the western room located on the second floor, plasterboard linings were cut just below the head track as shown in Figure 3 (a), representing partial-height lined, non-fire-rated partition walls. In comparison, both rooms located on the third floor utilized partition walls with full height lining. For full-height lining, the plasterboard extends to 20 mm below the steel deck/beam soffit, and the resulting gap is filled with fire-rated sealant, thus resulting in a fire-rated partition wall. In all rooms, base tracks were fixed to the bottom steel deck, and head tracks were fixed to either the beam or the steel deck; the steel studs then spanned between the base and head tracks. In both western rooms located on the second and third floors, steel studs were screwed to the base track but not to the head track, as shown in Figure 3. Not fixing the studs to the head track is typical practice in New Zealand construction as it enables the partition walls to slide inside the head track during earthquakes. In the eastern room located on the second floor, steel studs were screwed to both the base and head tracks, whereas on the third floor there was no connection between the studs and either the base or head tracks. Plasterboard linings were screwed to either one side of the studs (single-lined) or both sides (double-lined). A 10 mm gap was allowed between the bottom edge of the plasterboard and the top of the concrete slab to prevent crushing of the plasterboard during shaking.

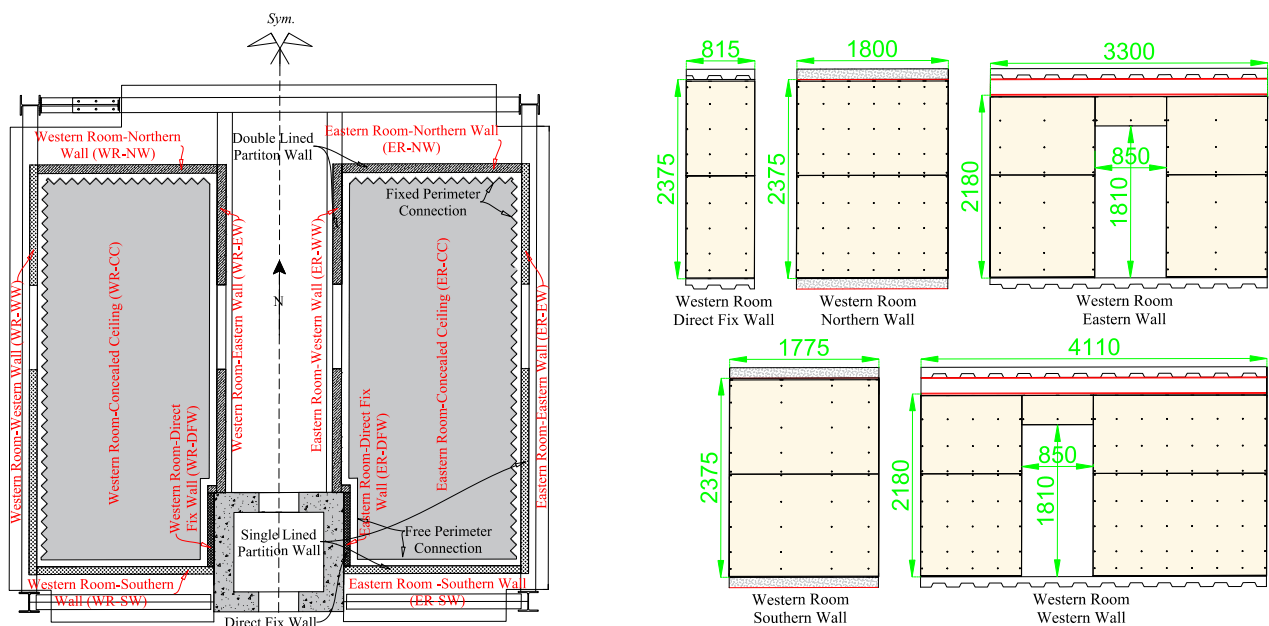


Figure 2: (a) Plan view of rooms; (b) Elevation views of partition walls in the west room.

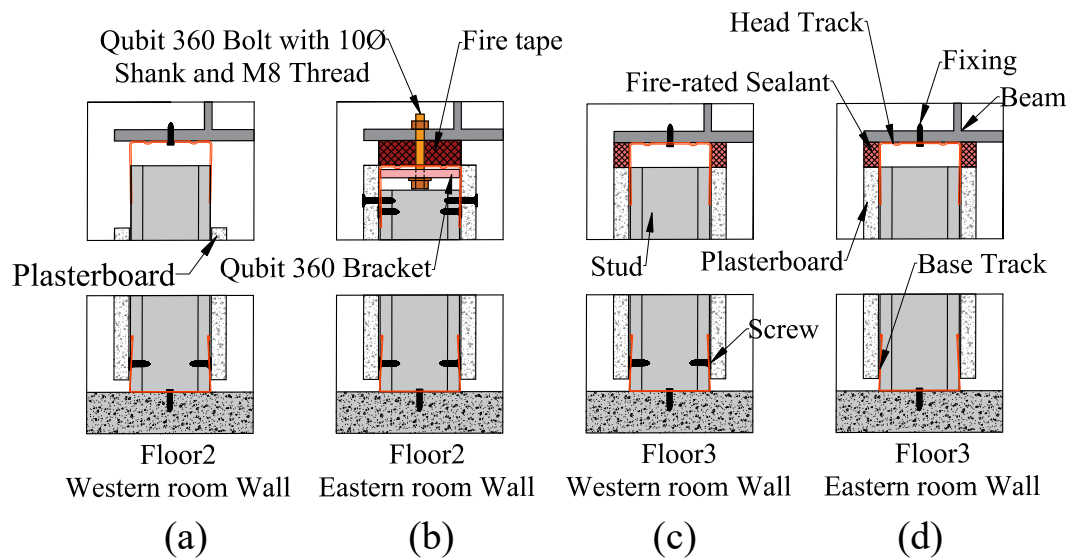


Figure 3: Top and bottom wall detailing.

In the eastern room located on the second floor, a low-damage partition wall system, ‘Qubit 360’, was used (Menegon et al., 2023a). In this system, instead of directly connecting the deflection head track to the slab above, flexible Qubit 360 brackets were inserted inside the head track and connected to the soffit using bolts, as shown in Figure 3(b). Large circular holes in the head track allow the bolts to move independently of the head track and transfer only nominal loads into the partition walls as the Qubit 360 brackets deform. It is also worth noting that in this system, the movement of the corridor wall (ER-WW) was decoupled from the concrete core walls by inserting a vertical gap, which was filled with fire-rated tape. The concept behind this system is to isolate partition walls from earthquake-induced inter-story drifts, thereby reducing damage to the partition walls.

At wall-to-wall junctions, three types of corner detailing were used, as shown in Figure 4. In the western rooms located on the second and third floors, the wall studs meeting at corners were fixed to each other, as shown in Figure 4(a). This represents common practice in New Zealand. In the Qubit 360 system, the corner detailing differs from that used in the western room in that an additional stud is installed to provide higher strength and stiffness to the wall corners, as shown in Figure 4(b). In the eastern room located on the third floor, a low-damage corner detailing, suggested by the Association of Wall and Ceiling Industries Code of Practice (AWCI, 2018), is used, as shown in Figure 4(c). In this detailing, instead of directly connecting the end studs to the return wall, it is nested inside a head track that is screwed to the return wall. Plasterboard lining is installed 20 mm short of the return wall and the resulting gap is filled with fire-rated sealant. This configuration allows the end stud to slide inside the head track, and thus to decouple the in-plane movement of the partition wall from the out-of-plane movement of the return wall. By minimising the displacement incompatibility at this location, the damage would be reduced.

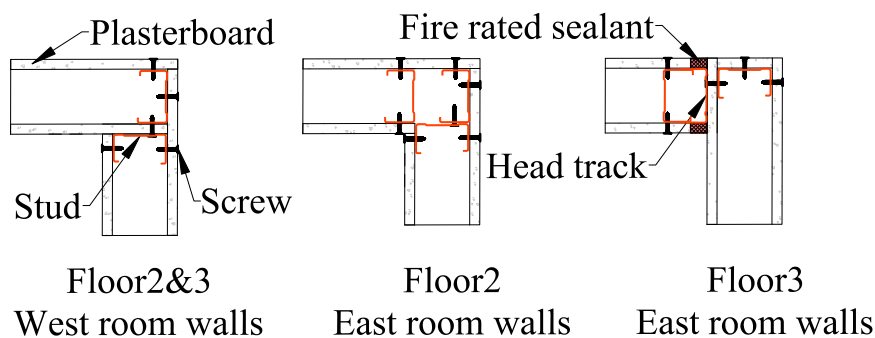
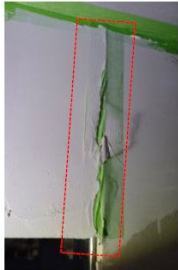
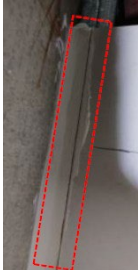
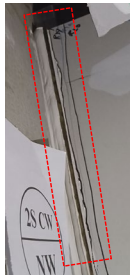
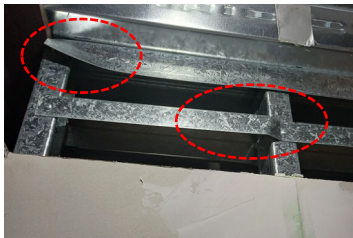


Figure 4: Corner detailing of partition walls.

4 DAMAGE OBSERVATIONS AND CLASSIFICATION

Between runs, the partition wall–ceiling systems were inspected, and damage was documented and captured through photographs. The different types of observed damage were then classified into three damage states, DS1, DS2, and DS3, in accordance with Miranda and Mosqueda (2011), based on the level of repair action required to restore them, as shown in Table 2.

Table 2: Examples of damage to partition walls.

Damage States	Representative Photos and Descriptions		
Superficial Damage (DS1)			
	(a). Warping or cracking of the paper tape and plasterboard (WR-WW wall on Floor 2 after Run 8).	(b). A small number of screw impressions (WR-SW wall on Floor 2 after Run 16).	(c). Minor separation at the corner joint sealant (WR-EW wall on Floor 2 after Run 16).
Moderate Damage (DS2)			
	(d). Opening and crushing of the plasterboard at panel interfaces (WR-WW wall on Floor 2 after Run 23).	(e). Plasterboard detachment and crushing at screw locations (WR-WW wall on Floor 3 after Run 23).	(f). Major separation at the corner joint sealant (WR-EW wall on Floor 2 after Run 20).
Critical Damage (DS3)			
	(g). Popping out of studs from the base track and local damage to studs (ER-EW wall on Floor 3 after Run 24).	(h). Residual displacement of the wall (ER-EW wall on Floor 3 after Run 24).	(i). Buckling of noggings and bending of the head track (WR-NW wall on Floor 2 after Run 24).

DS1 is related to superficial and cosmetic damage, such as damage to the paint, joint compound, and paper tape caused by screw impressions or cracks at the corner joints or corners of wall openings. This type of damage can affect the aesthetic functionality of the partition walls, but the fire rating, acoustic performance, and stability of the wall are likely to be preserved. This type of damage can be repaired using light plastering, taping, and repainting.

DS2 corresponds to local damage and detachment of the plasterboard from the framing. This damage can occur in the form of crushing where screws have pulled out, at the wall toes, where plasterboard is compressed by the rocking motion of the wall, or separation of panels at their interfaces. Additionally, in DS2, major separation is observed at the corner joint sealant. DS2 can partially affect the fire and acoustic rating performance of the walls and impact their aesthetic performance; however, the stability of the wall is still preserved. To restore a partition wall that has sustained DS2 to its original condition, the corner joint sealant and damaged plasterboard panels need to be removed and replaced, followed by plastering, taping, and repainting of the walls.

In DS3, the framing elements of the partition wall (i.e., studs, tracks, and noggings) sustain damage such as warping or buckling. In this type of damage, the damaged elements need to be removed and replaced; then plasterboard panels are installed, followed by plastering, retaping, and painting to restore the partition wall to its original condition. Removal of parts or the entirety of the suspended ceiling may be required to gain access to the framing elements, making the repair process challenging. This type of damage can impact the stability of the walls in addition to their fire-rating and aesthetic performance. Furthermore, doors in partition walls that have sustained DS3 are likely to become jammed due to residual displacement and deformation of the framing elements. With respect to functionality, it is unlikely that partition walls experiencing DS3 pose a life-safety risk to occupants; however, to restore the fire-rating performance of the partition walls, repairs beyond temporary measures may be required.

5 DISCUSSION

After Run 24, all partition walls and ceilings were assessed in terms of damage state, and the results are summarized in Figure 5. As can be seen, the partition walls of the second-floor eastern room performed very well and suffered much less damage in comparison to the other partition walls. This underscores the effectiveness of the low-damage Qubit 360 system in isolating partition walls from inter-story drift demands (as schematically shown in Figure 6), thereby mitigating damage to them. The limited observed damage to these partition walls was restricted to screw pull-out and paper tape warping. Although partial detachment of plasterboard linings was observed in these walls, there might be no need for plasterboard replacement due to the limited extent of damage.

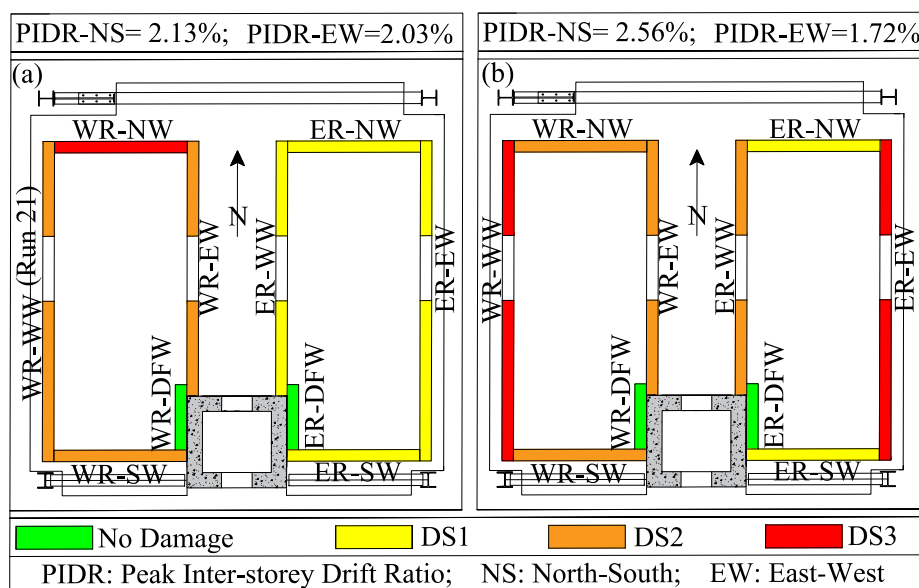


Figure 5: Damage states of partition walls located on (a) Floor 2 and (b) Floor 3 after Run 24.

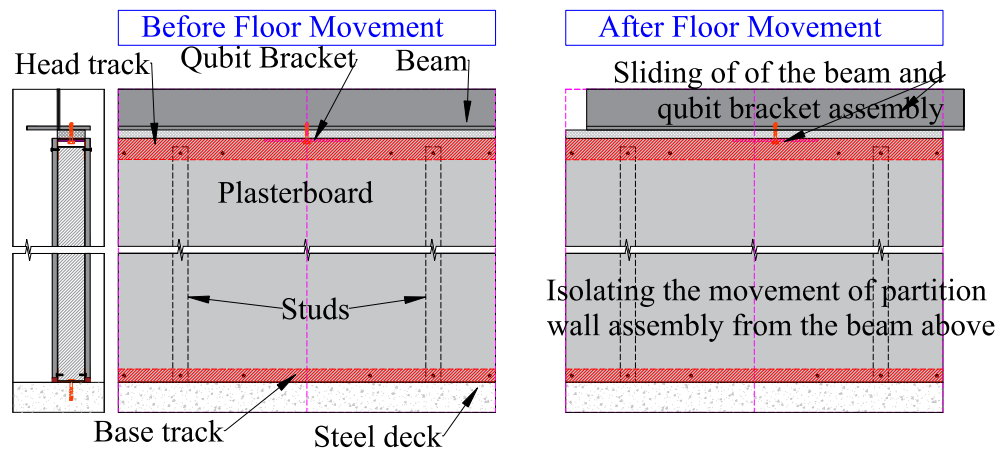


Figure 6: Mode of movement of the partition walls in the N-S direction in the Qubit 360 system in the eastern room on the second floor.

Partition walls oriented in the N-S direction in the third-floor eastern room performed poorly. Specifically, in the Eastern Room–Eastern Wall (ER-EW), corner studs popped out of the base tracks, as shown in Table 2 (g). In addition, this partition wall experienced residual displacement, as illustrated in Table 2 (h). These damage modes were specific to this partition wall and are the result of having no connection between the studs and the base track. Lack of this connection allows the partition wall assembly to slide within the base track (instead of the head track) during shaking, as schematically illustrated in Figure 7. It appears that the friction forces between the plasterboard and the sealant, as well as those between the studs and the head track at the top, were greater than the friction forces between the studs and the base track at the bottom. Furthermore, because this partition wall is single-lined, its studs are more susceptible to torsional buckling compared to the studs in similar double-lined partition walls. In addition, implementing low-damage corner joint detailing at both ends of this partition wall creates a condition in which the return walls at the ends of the partition wall cannot effectively restrict its in-plane sliding during shaking, contributing to the development of residual displacement. In contrast, the partition walls oriented in the E-W direction in the third-floor eastern room (ER-NW and ER-SW) experienced significantly less damage compared to the other walls in this room (ER-WW and ER-EW). This is primarily due to the implementation of the low-damage corner joint detailing at both ends of these walls. Such detailing isolates the in-plane drift of the partition wall from the out-of-plane drift of the intersecting partition wall, thereby preventing the transfer of inter-story drift demands between them. Additionally, the in-plane sliding of these walls was restrained at both ends by the return walls, preventing the development of residual displacements. Consequently, damage to these walls was limited to minor screw impressions in the plasterboard and slight separation of the corner joint sealant.

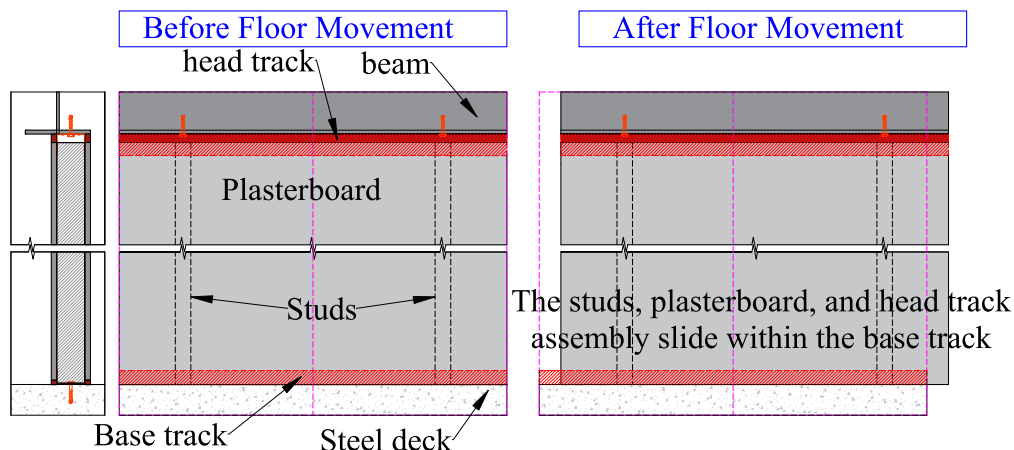


Figure 7: Mode of movement of the partition walls in the N-S direction in the eastern room on the third floor.

For the partition walls located in the western rooms on both floors, the predominant damage modes consisted of screw impressions, localized crushing of plasterboard around screw locations, and separation of the plasterboard from the sealant where sealant joints were used, as shown in the corresponding figures in Table 2 (e) and (f). In the WR–NW partition wall on the second floor, bending of the head track and local buckling of the noggings at both ends of the wall were observed, as shown in Table 2 (i). In contrast, no such damage was observed in the corresponding wall on the third floor. This difference can be attributed to the use of partial-height plasterboard lining in the second-floor partition wall, compared with the full-height lining combined with fire-rated sealant used on the third floor. During shaking, when inter-story drift in the N–S direction imposes out-of-plane drift on the WR–NW partition wall, this out-of-plane drift is transferred to both intersecting walls (WR–WW and WR–EW partition walls) through corner joints, dragging them along. This caused the two intersecting walls (WR–WW and WR–EW partition walls) to rock in order to accommodate the imposed in-plane drift, as schematically illustrated in Figure 8. Because partition walls on the second floor used partial-height plasterboard lining, there was no effective restraint at the top of the wall; consequently, the resulting uplift was sufficiently large to induce local bending in the flange of the head track at the corner joint intersections. Conversely, on the third floor, the use of full-height plasterboard combined with fire-rated sealant provided top restraint to the wall assembly, limiting uplift and thereby preventing significant bending of the head track at the end studs of the return walls in the WR–NW partition wall.

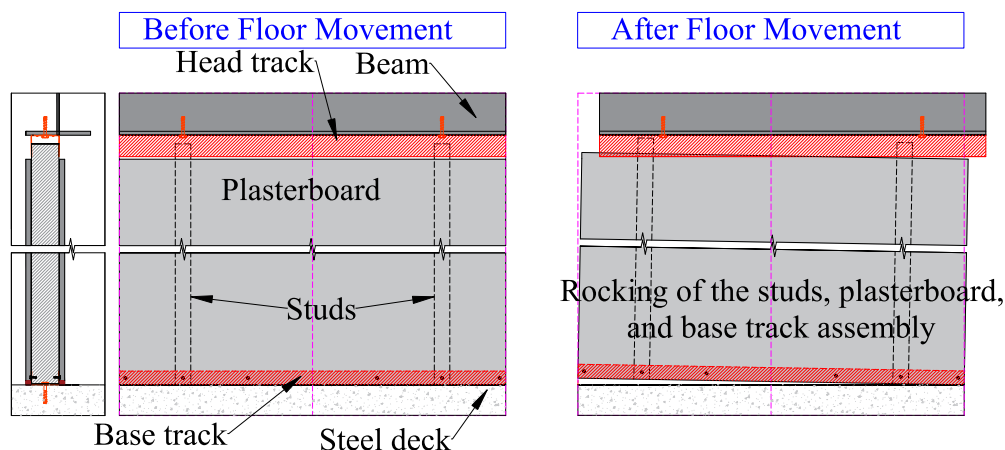


Figure 8: The rocking mode of movement of the partition walls in the N–S direction in the western room on the second floor.

Another difference observed between the partition walls of the western rooms on the second and third floors was that crushing of the plasterboard at the screw locations was more severe on the third floor (as shown in Figure 9), despite there being no considerable difference in the inter-story drift demands. It appears that this difference is also related to the use of full-height plasterboard linings combined with fire-rated sealant in the partition walls of the third-floor western room, as opposed to those on the second floor. In fact, the presence of a full-height wall with fire-rated sealant not only transfers friction forces from the soffit to the wall due to inter-story drift but also restrains the wall from accommodating the drift transferred from the return walls through rocking and uplift mechanisms. Consequently, the studs are forced to bend to accommodate the imposed drift demand, as schematically illustrated in Figure 10. When the studs bend, they are not only more likely to sustain damage themselves but also slide relative to the plasterboard, resulting in the screws crushing the plasterboard. This mechanism intensifies damage to the plasterboard and studs in these walls compared to the partition walls in the western room on the second floor, where the walls can more readily accommodate the drifts imposed by the return walls through uplift and rocking mechanisms due to the use of partial-height plasterboard linings.

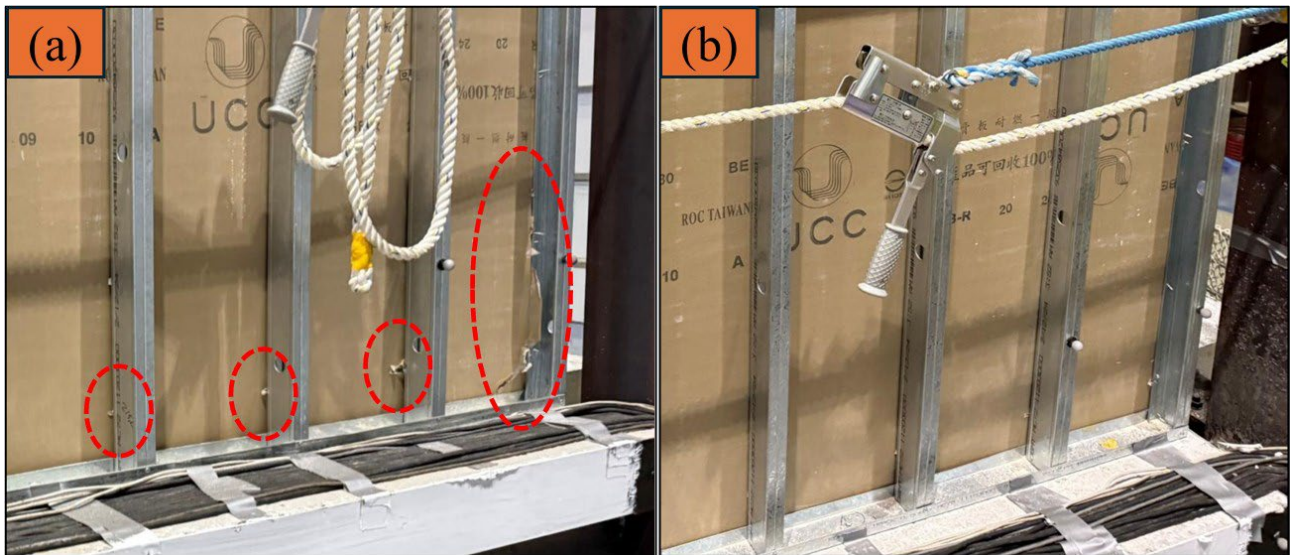


Figure 9: Damage observed in the plasterboard of the WR–WW walls after Run 23, located on (a) Floor 3 and (b) Floor 2.

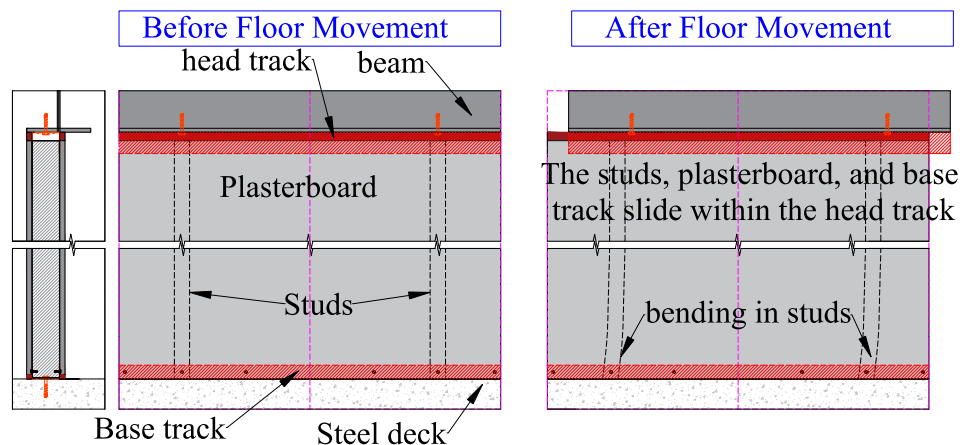


Figure 10: Mode of movement of the partition walls in the N–S direction in the western room on the third floor.

6 CONCLUSIONS

A joint research project between QuakeCoRE (New Zealand) and the National Centre for Research on Earthquake Engineering (NCREE, Taiwan) was initiated to investigate the seismic performance of a five-story building with various non-structural elements. One of the objectives of this project was to examine the seismic performance of partition wall–ceiling systems with different construction details, considering their interaction with structural elements. The seismic performance of partition walls was investigated under various levels of seismic demand by applying 3D excitations at the base of the building using a large-scale shake table. Several observations were made regarding the modes of movement and damage of partition walls, based on which conclusions were drawn and are summarized as follows:

- The absence of connections between the studs and the base and head tracks can cause partition walls to become displaced and studs to pop out of the base track during shaking, necessitating major repair actions to restore the walls.
- Differences in the types and extents of damage, as well as modes of failure, were observed in the western rooms located on floors 2 and 3. These differences appear to be attributed to differences in the height of the plasterboard linings in these two rooms.

- The low-damage Qubit 360 system not only delayed the initiation of damage to higher drift levels but also reduced the extent of damage by isolating the partition walls from inter-story drifts.
- The implementation of low-damage corner joint detailing can be effective in mitigating damage, provided that the in-plane sliding of the wall is restricted by boundary structural or non-structural elements at both ends, thereby limiting residual displacement in the partition wall.

7 ACKNOWLEDGEMENTS

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