SHAKE TABLE TEST OF A BALLOON-FRAMED, COLD-FORMED STEEL FAÇADE WITH DRIFT CLIPS

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Abstract: *Interstory drift is a primary cause of seismic damage to building elements that span vertically between floor levels, such as exterior façade walls. To study this issue, a recent shake table test of a full-scale 10-story mass timber building at the NHERI@UC San Diego facility included a three story cold-formed steel, balloon-framed exterior façade subassembly. The building was designed for seismic resilience, so the subassembly employed clips that slide within a horizontal track to isolate the response of the façade from the interstory drift demands of the structure. This paper discusses the experimental results of the subassembly during the shake table test program. Subassembly movement and the building's response are compared to evaluate the effectiveness of the drift clip system.*

Preliminary observations show that the drift clips largely isolate the façade's in-plane response from the structure as intended, significantly reducing interstory drifts and associated damage imposed on the subassembly by the structure. However, binding action caused screw pull-out at some clip connections on the uppermost floor over the course of repeated earthquake excitations. These connections were replaced midway through the testing program, and the number of clips and their capacity were increased. Over the course of numerous large ground motions, many more than what a typical building would be expected to experience, limited damage continued to occur at these locations. The damage that did occur did not affect the overall function of protecting the façade; damage to sheathing, windows, and exterior cladding was avoided altogether. Notably, incorporating a vertical joint at the corner of the two perpendicular façade sections solved the issue of perpendicular drift-compatible walls impacting one another. Lessons learned offer valuable insight towards improving the design and detailing practice of future assemblies considered for implementation in buildings.

1. Introduction

Resilient seismic design requires buildings that minimize earthquake damage and facilitate quick recovery post-disaster (Fischer et al. 2017). In this regard, damage to nonstructural systems that prevents a building from being used for its essential functions after an earthquake constitutes a system-level failure, even when the structure remains intact. Di Lorenzo and De Martino (2019) calculated that the economic effects of downtime due to earthquake damage can exceed the replacement cost of a building. Seismic damage to the nonstructural components themselves can also impose a significant cost; Taghavi and Miranda (2003) calculated that nonstructural components typically account for 65% to 85% of the total cost of a building. Improving the performance of nonstructural components is therefore essential to maximize the likelihood of rapid recovery post-earthquake and minimize damage and costs.

In 2023, the NHERI TallWood project completed a capstone test of a 10-story mass timber building, designed with a post-tensioned rocking wall lateral system. The structural system was designed with resilience objectives, to sustain no damage up through shaking with a 975-year return period, and repairable damage at MCER level shaking (Pei et al. 2023). Likewise, the design of the building's nonstructural components, including the exterior façades, aimed for no more than minor damage at design level shaking (475-year return period), and repairable damage at 975-year return period and beyond (Pei et al. 2023). The shake table test program included four exterior façade subassemblies installed on the lower three stories of the 10-story mass timber building: cold-formed steel (CFS) platform-framed, balloon-framed, and spandrel-framed exterior wall façades and a stick-built glass curtain wall. A variety of details were implemented in these facades with the aim of identifying which could meet the resilience objectives defined above. This paper focuses on the balloon-framed CFS subassembly, which demonstrated unique features, both in design and performance, that merit an in-depth treatment separate from the other subassemblies.

CFS-framed walls often suffer from significant seismic damage, resulting in high economic costs and threats to occupant safety (Di Lorenzo and De Martino, 2019). However, while there has been some research on interior partition walls, little research has been conducted on CFS-framed exterior walls and façades (Fiorino et al. 2019). In the only known shake table test that has examined the seismic performance of a balloon-framed CFS façade designed to be entirely nonstructural, Pantoli et al. (2016) observed extensive damage to the clips that attached the façade to the building for shaking in the in-plane direction, with roughly 80% of the clips detaching completely. In addition, damage to interior sheathing and the exterior finish at the corners of the test building initiated at about 0.56% drift, with extensive corner tearing of the exterior finish along the nearly a full story height by the completion of testing.

For the present experiment, the design priorities were to reduce damage to the clips and to accommodate relative movement of the façade walls at the corner, both of which are integral to maintaining the façade resiliency. The façade was designed with a sliding clip system and a large capacity hinged expansion joint cover at the corner. The objective of this paper is to evaluate the performance of the balloon-framed façade assembly in the context of the resilience objectives.

2. Testbed Building

The exterior façade subassemblies were examined in the context of a full-system configuration and were attached to a full-scale, 10-story (34 m tall) mass timber building (Fig. 1a). The building employed post-tensioned mass timber rocking walls as its primary lateral load resisting system, and U-shaped flexural plates between the rocking walls and bounding columns were the system's primary means of dissipating energy. This

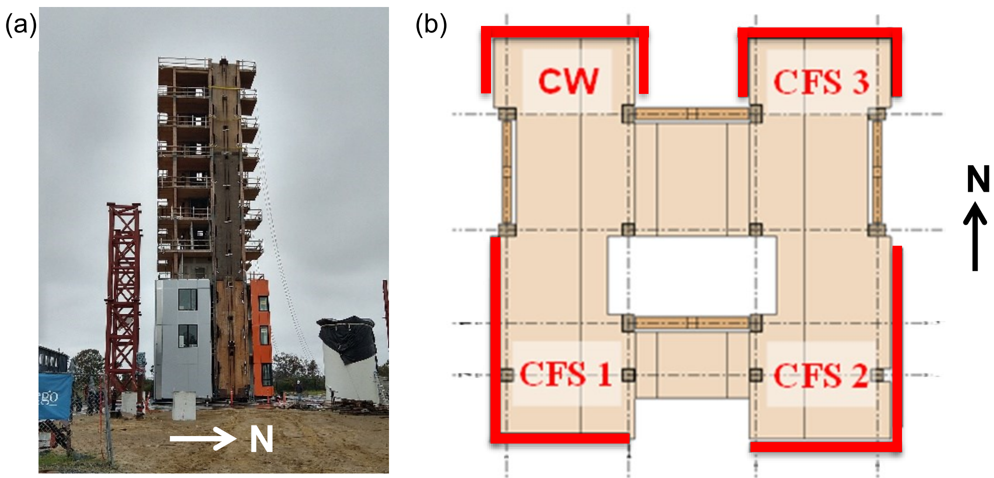

Figure 1: (a) 10-Story building specimen and (b) floor plan showing the platform-framed (CFS 1), ***balloon-framed (CFS 2)****, and spandrel-framed (CFS 3) subassemblies as well as a stick-built glass curtain wall (CW)*

building was particularly well suited for an experiment with drift sensitive components such as nonstructural walls, because rocking walls can accommodate large earthquakes without damage (Pei et al. 2019). This type of lateral force resisting system increases the flexibility of the building, resulting in a comparatively large drift response (Zhou et al. 2012). This structural configuration emphasized the need for exterior façade wall elements that can likewise accommodate building interstory drift without damage.

An exterior façade wall subassembly was located at each corner of the building (Fig. 1b), which had a footprint that measured approximately 10.5 m by 10.5 m (34' by 34'). The CFS façade subassemblies extended over the first three stories of the building. The first story was 3.96 m (13') tall, and the remaining stories were 3.3 m (11') tall. The lower two floor diaphragms were cross-laminated timber (CLT), and the upper diaphragm was glue-laminated timber (GLT).

Tests were conducted at the large-scale shake table facility NHERI@UC San Diego during early 2023. A total of 88 shake table tests were conducted using nine different ground motion records, scaled to 43-year, 225-year, 475-year and 975-year return period, as well as risk-targeted maximum considered earthquake (MCE_R) hazard levels. Tests were denoted as MID13 (motion ID) to MID100. The complete test program is documented in Wichman (2023).

3. Balloon-framed Subassembly

3.1. Description and Dimensions

The exterior façade subassembly (Fig. 2) was comprised of two walls in an L-shaped configuration that use CFS studs with balloon framing. Also called bypass framing, balloon framing consists of long studs that span multiple stories and are connected to the outside of the building via CFS clips. The subassembly was framed with 600S162-43 studs spaced 406 mm (16") on center with 600T125-43 header and base tracks. Framing member dimensions are given in Table 1. The footer track was attached to a concrete foundation with 15.9 mm (5/8") knurled powder driven pins and to the steel ledger with 6.2 mm x 76 mm (¼" x 3") screw anchors, while the header track formed the top of a parapet wall. The concrete foundation was directly post-tensioned to the shake table platen. The subassembly contained five windows: three 0.91 m by 1.52 m (3' by 5') on the south side and two 1.52 m by 2.13 m (5' by 7') on the east side. Window framing members (headers, jambs, and sills) used 16-gauge steel instead of the 18-gauge used for typical members.

Table 1: Cold-formed steel member dimensions

Member Type	Standard Designation	Web, mm (in.)	Flange, mm (in.)	Thickness, mm (in.)
Typical Wall Stud	600S162-43 (33)	152 (6)	41 (1.625)	1.09 (0.043)
Header and Footer Track	600T125-43 (33)	152 (6)	32 (1.25)	1.09 (0.043)
Window Jambs	600S200-54 (50)	152 (6)	51 (2.0)	1.37 (0.054)
Window Sills	600T125-54 (50)	152 (6)	32 (1.25)	1.37 (0.054)
Window Header	CEMCO Pro-X 600XTC425-54 (50)	152 (6)	107 (4.25)	1.37 (0.054)

Wall dimensions are given in Fig. 2. The wall was sheathed with 12.7 mm (1/2") gypsum wallboard on the inside and 18-gauge, 12.7 mm (1/2") sheet steel and gypsum composite wallboard (CEMCO Sure-Board® Series 200 Structural Shear Panels) on the outside. To provide the shear strength, the panels were attached to the framing with #8 screws spaced 152 mm (6") o.c. The exterior was clad with lightweight ACM (aluminum composite material) panels that were attached to the exterior sheathing with aluminum clips.

To prevent the clip damage observed by Pantoli et al. (2016), this specimen used sliding clips, namely Simpson Strong-Tie DSSCB46 drift clips (Daudet 2021), which as configured are intended to slide horizontally within a U-strut attached to the edge of the floor slab. Three #14 shouldered screws were used for each clip, one in each of three vertical slots. The slotted configuration prevents forces from vertical deflections of the building diaphragm from being transferred to the exterior façade walls, which are not typically designed to support such forces. The U-strut was attached to the edge of the slab with 8 mm diameter, 54 mm threaded length screws spaced 143 mm (5 5/8") on center (Fig. 3a). Care was taken to attach to side grain for the two CLT levels, but

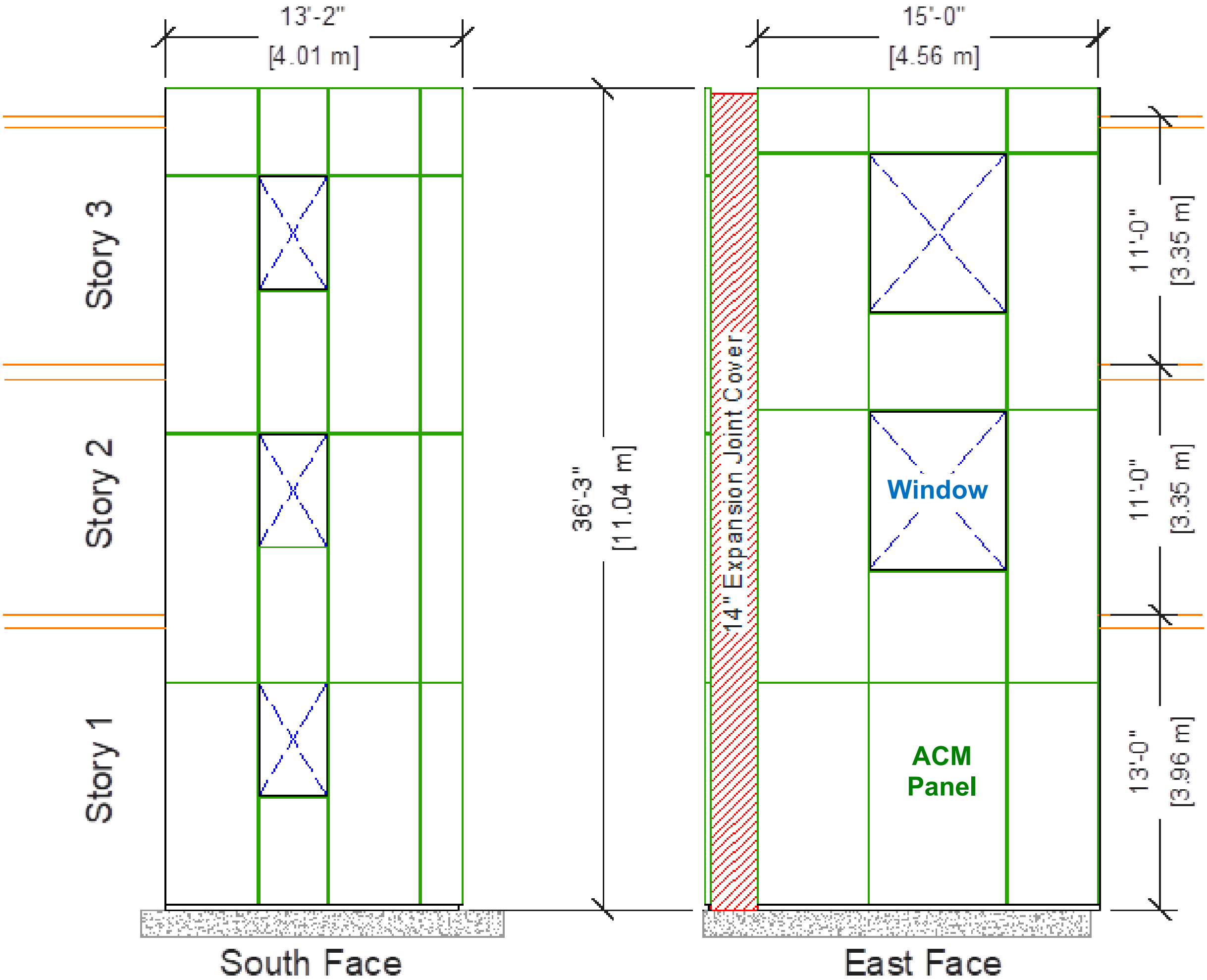

Figure 2: Balloon-framed subassembly elevation view and dimensions

on the south side of the GLT level only end grain connection was available. Tests were conducted by Simpson Strong-Tie (2023) to ensure that the end grain connection is sufficiently strong. The clips allow in-plane relative motion between the wall and the structure while still resisting out-of-plane forces. Notably, the clips were developed and anticipated to be used for life safety; however, an objective of the present study was to determine if the resilience objectives could be met using these clips and other enhanced details.

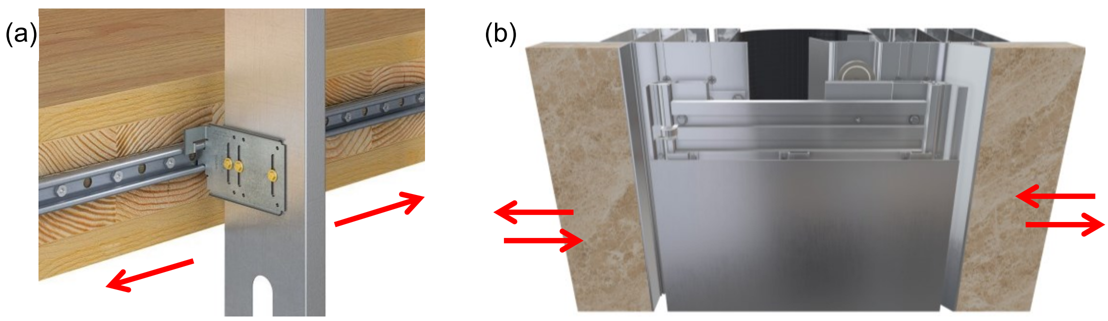

Figure 3: Drifts are accommodated using (a) DSSCB clips by Simpson Strong-Tie and (b) XLP-2G-1400 expansion joint cover by Construction Specialties

If each exterior wall is free to slide relative to the building in its own plane, an incompatibility arises at wall intersections when perpendicular walls separate and impact one another (Hasani and Ryan, 2021). For all CFS facade configurations, the incompatibility was resolved by separating the perpendicular wall segments so that they would not come in contact with one another under design drifts, then bridging the gap with an expansion joint. A particularly large expansion joint was required for the balloon-framed subassembly, wherein interstory drifts accumulate over multiple stories. An XLP-2G-1400 expansion joint cover by Construction Specialties was chosen (Fig. 3b), which consists of a modular hinged cover with an integrated magnet and pulley system that allows for expansion and contraction and recloses after the motion.

3.2. Special Design Considerations

A typical exterior façade wall transfers seismic forces to the building at each level, but isolating the wall from building drift with drift clips means that in-plane lateral loads in the wall are not transferred to the building. Instead, the wall must be able to support its own seismic forces, which, in a balloon-framed system, accumulate over multiple stories (Fig. 4a). Each side of the subassembly was designed as an independent shear wall, so the design incorporated holdowns anchored to the foundation and back-to-back bounding studs (Fig. 4b) and the sheet steel-gypsum composite sheathing described above to increase the wall's shear and overturning resistance.

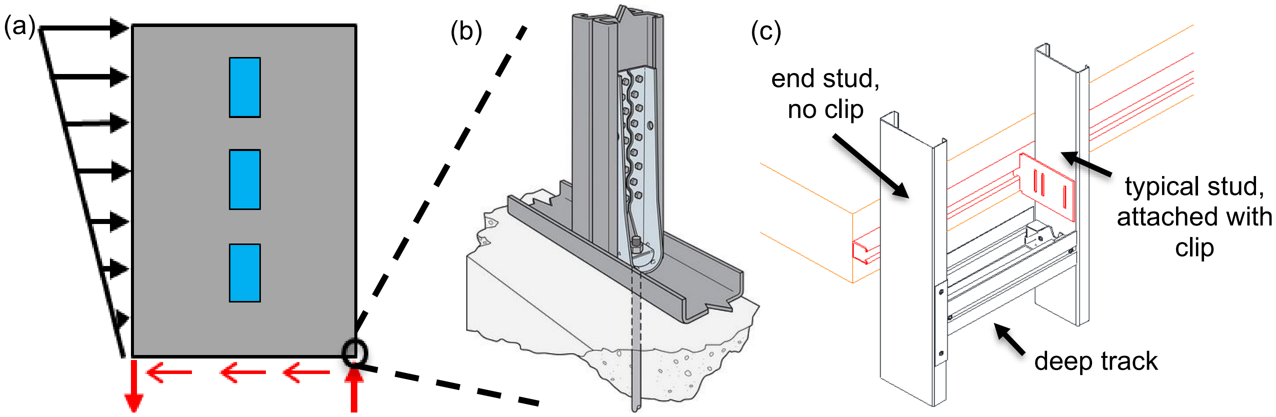

Figure 4: Special design considerations and detailing

Accumulation of drift and forces limits the number of stories for which using balloon framing with drift clips is practical. Buildings with many stories would need the framing to "start over" after some number of stories, separating the balloon-framed façade into separate, vertically distributed units. Stacked sections would require horizontal slip/drift joints in the framing to accommodate movement between the sliding top of a lower section and the fixed base of another.

Under seismic excitation, the clips are designed to slide back and forth, and clips that are too close to the end of the U-strut may slide out of its open end and prevent the wall from recentering. To resolve this, the end studs did not use clips and were not attached to the diaphragm directly. Instead, they were attached to the nearest stud with short, deep track sections that cantilevered the end stud from the rest of the wall (Fig. 4c).

3.3. Instrumentation

The response of the building specimen was measured via accelerometers directly attached to the floor diaphragms, and interstory drifts were derived by integrating the accelerations for floor displacements and subtracting the displacements between stories. Accelerometer signals were noisy and sensitive to filtering parameters, therefore there is some uncertainty in the final processed interstory drift histories. Wall slip relative to the floor diaphragm was measured via horizontally oriented string potentiometers connecting the wall to the floor diaphragm (Fig. 5). These potentiometers were located near the midpoint of each wall segment.

Figure 5: String potentiometer used to measure subassembly slip relative to the building

4. Observations from Component Damage

4.1. Attachment Clips

The primary goal of this research was to evaluate whether using drift clips reduces seismic damage. Over the course of 42 design level or larger earthquakes, the walls suffered little damage as interstory drift demands reached up to 1.38% during the shake program (Table 2). The subassembly was designed to accommodate design building interstory drifts of up to 2.5%. However, experiment drifts were lower than predicted because additional mass could not be added to the specimen as originally intended. Another factor is that, given the design, the final ground motion selection was somewhat conservative so that the building could survive multiple phases of testing, which are still ongoing as of the time of writing. The drifts imposed by the building were enough to identify deformation mechanisms and initial damage modes of the subassembly, but ultimate limit states could not be determined from these tests.

In the prior mentioned Pantoli et al. (2016), tests with interstory drifts of 0.94% and 1.41% resulted in drywall cracking and fracture, drywall screw pull-out, tearing at corners, stucco bulging, and detachment of up to 15% of the attachment clips. Conversely, in this study neither drywall damage nor damage to the exterior cladding were visible by the end of the test program. However, after reaching the 475-year hazard level, some of the attachment clips, mostly on the fourth floor where slip between wall and building were the largest, started detaching from the studs due to screw pull-out. Videos of the clips show that they bound in the U-track, causing the clips to bend before slip occurs. Because of this, screws nearer the U-track pulled out before screws further away. Additionally, a few clips were damaged due to errors in installation. However, the wall was still solidly attached and there were no life safety concerns at this point.

Table 2: Maximum interstory drift of the building on subassembly levels

Story	South Side	East Side
3	1.27%	1.17%
2	1.38%	1.13%
1	1.17%	0.95%

After damage was observed (MID37), clips were reinstalled at locations where screw pull-out had occurred or initiated. Most connections on the fourth floor were reinforced in several ways to increase resistance to screw pull-out and increase system redundancy. Two screws were installed in the slot closest to the U-strut (Fig. 6a). Where possible, a 12-gage backing strap was added to increase pull-out strength (Fig. 6b), and a second clip was installed on the open side of the stud using a track section attached to the stud flanges (Fig. 6c).

(a) (b) (c)

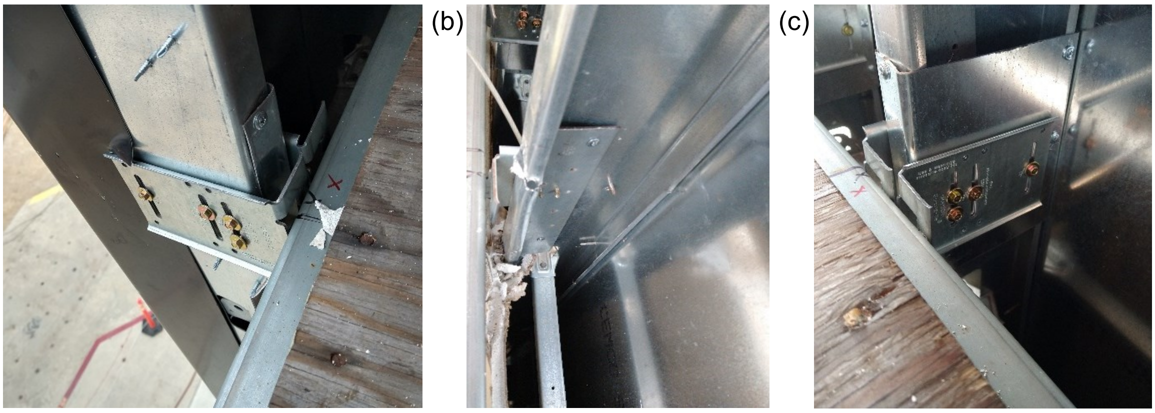

Figure 6: Clips were reinforced by (a) using additional screws, (b) adding backing material, and (c) adding a second clip to studs using a short track

After the repair, damage continued to concentrate at the same clip locations, but the modes of failure became more varied, including screw pull-out, screw tear out, stud bending, and stud buckling (Fig. 7). All of these failure modes can be attributed to binding action. Screw pull-out was the most common mode of damage and signs of incipient pull-out were observed soon after the repair. Unlike before the repair, screw pull-out did not occur during single tests but instead progressed slowly over multiple tests (Fig. 7a). Many of the reinforced clips on the fourth floor and almost all of the original clips on the second and third floors survived the testing program without damage, and after reinforcement the clip system exhibited sufficient redundancy and resiliency to survive many large shakes and prevent damage from propagating to the wall itself.

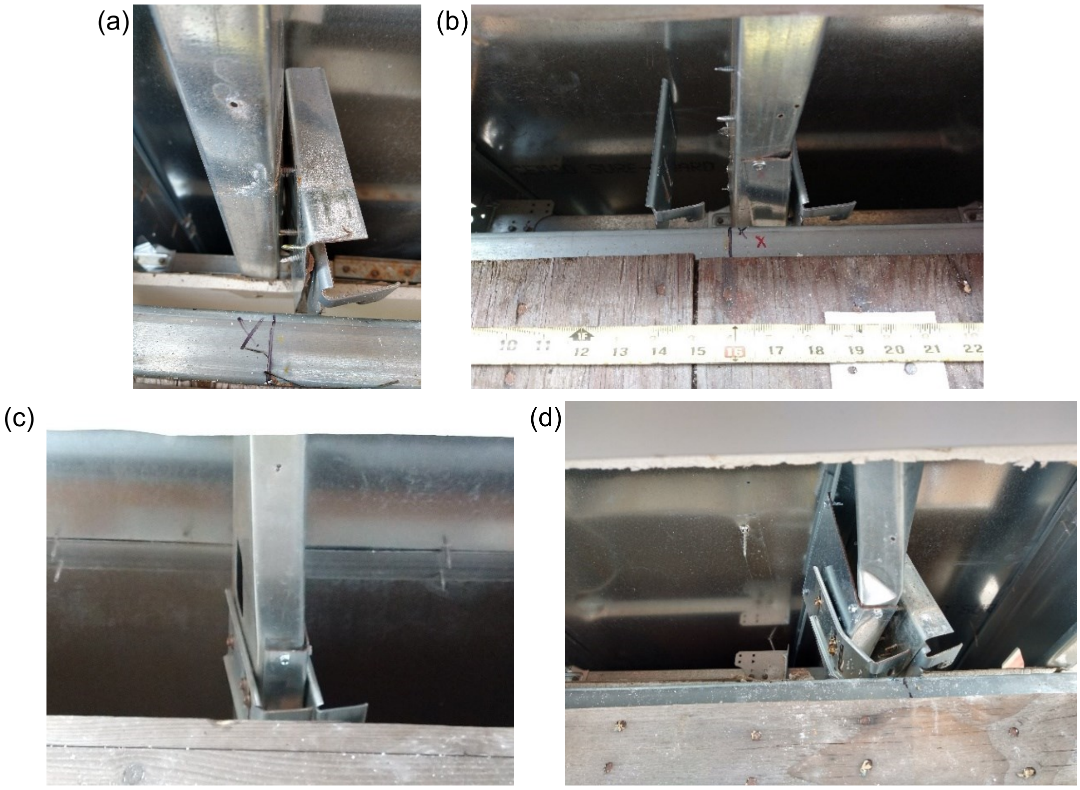

Figure 7: Damage modes included (a) incipient and (b) full pull-out, (c) stud bending, and (d) stud buckling

In general, signs of damage to clips appeared within a few large shakes. Stud bending and buckling did not occur until the MCE_R ground motions (MID88). Studs, unlike clips, cannot be repaired without deconstructing the entire subassembly, so designing clips to pull-out before they cause stud damage could be advantageous. Clips that showed no signs of stress after a few earthquakes remained undamaged for the remainder of the testing program, suggesting that resolving binding issues would eliminate most of the damage observed during the testing program.

4.2. Corner Expansion Joint

No damage occurred at the intersection between the two wall segments. The expansion joint cover was able to open and close as the subassembly slipped relative to the building in both directions, and the joint cover returned to its nominal position after shaking concluded. Figure 8 shows how the expansion joint opens. The joint could close up to 260 mm (10.25”) before contact between the two wall segments occurs; of this, 86 mm (3.40”) was the maximum observed movement (gap closure/compression). It should be noted that the maximum slip, 128 mm (5.03”), was in the E-W direction, which shows that a greater portion of the joint capacity might have been used if the building had been oriented differently relative to the ground excitation. The movement capacity in the direction perpendicular to the joint cover (lateral) was designed to be equivalent or greater than the in-plane movement (tension/compression). Overall, the high capacity relative to demand occurred because the joint was designed for larger drifts than those actually experienced during the test program. Nevertheless, the lack of damage to the walls demonstrates that placing an expansion joint between perpendicular wall segments is an effective solution for mitigating corner damage.

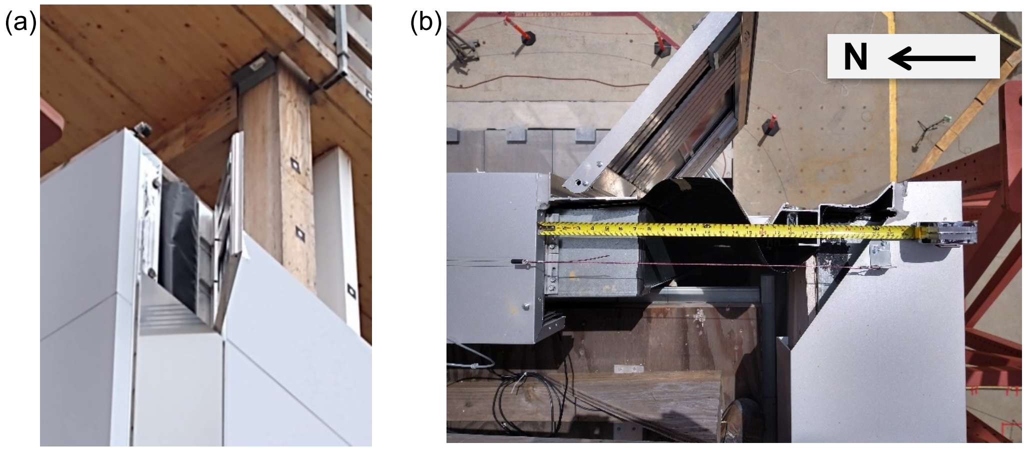

Figure 8: Corner expansion joint corner after opening viewed from (a) outside and (b) above

5. Structure Response vs Subassembly Response

5.1. Time History Analysis

A key question was whether the exterior wall would follow the response of the structure or vibrate as an independent component. A subassembly with frictionless slip between the drift clips and the U-strut would have a response that depends solely upon its own dynamic properties; however, friction and binding between the clips and the U-strut could couple the response of the wall to the building.

Figure 9 shows an interstory drift time history of the subassembly compared to the structural interstory drift in the same direction taken from MID46, a bidirectional motion taken from the 1999 Chi-Chi earthquake, TCU075 station, scaled to 475-year hazard level. This time history demonstrates typical behaviors of the subassembly observed throughout the testing program. Subassembly motion was computed by subtracting slip measured by the string potentiometers between the wall and building from the story displacements derived from accelerometer measurements. The corresponding time history of the slip response is shown in Fig. 10. When structural interstory drifts were smaller at the beginning and end of an individual test, the subassembly's response matched that of the structure and negligible slip was observed. As structural interstory drifts increased in amplitude, the subassembly began to slip relative to the building (Fig. 10), and subassembly interstory drift decreased relative to building interstory drift (Fig. 9).

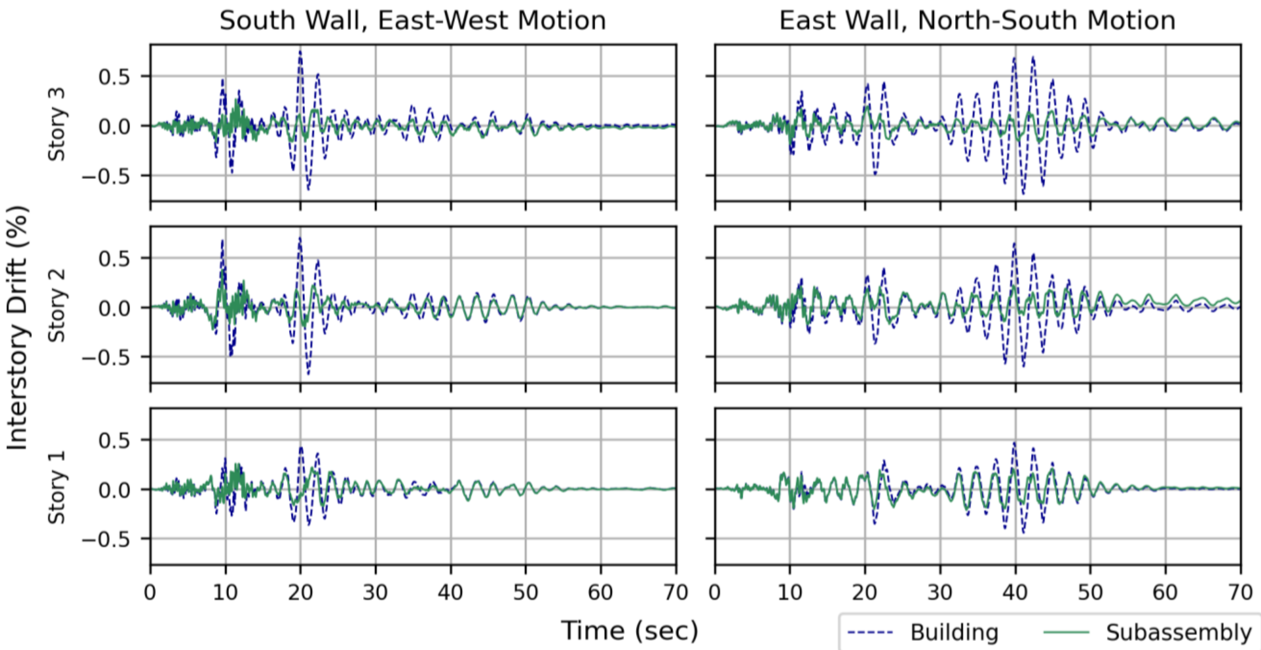

Figure 9: Representative interstory drift response of balloon-framed subassembly compared to building interstory drift for 475 Chi-Chi XY

Despite slipping, the response of the subassembly remained in phase with the building, which indicates that even when slip was occurring, friction between the drift clips and the U-strut the wall was not fully uncoupled from the structure's motion. An advantage of this effect is that staying in phase reduces the differential movement between the wall and building that could occur if the wall were to oscillate out of phase with the building, which would be more likely to exceed the limits of movement between the exterior wall and other building components.

The interstory drift time histories for the three stories each had roughly the same amplitude while the slip response increased with the height of the building. This is an indicator that the sliding clip mechanism does not activate due to interstory drift. Instead, interstory drifts accumulate over multiple stories, meaning that for constant interstory drift the difference between subassembly and building displacement is roughly three times as high for the third story than the first. The slip response was not perfectly proportional to height because the friction between the clips and the U-strut prevented slipping until the difference in floor displacement was sufficiently large. As a result, on portions of the slip history the upper story slips while the lower story does not.

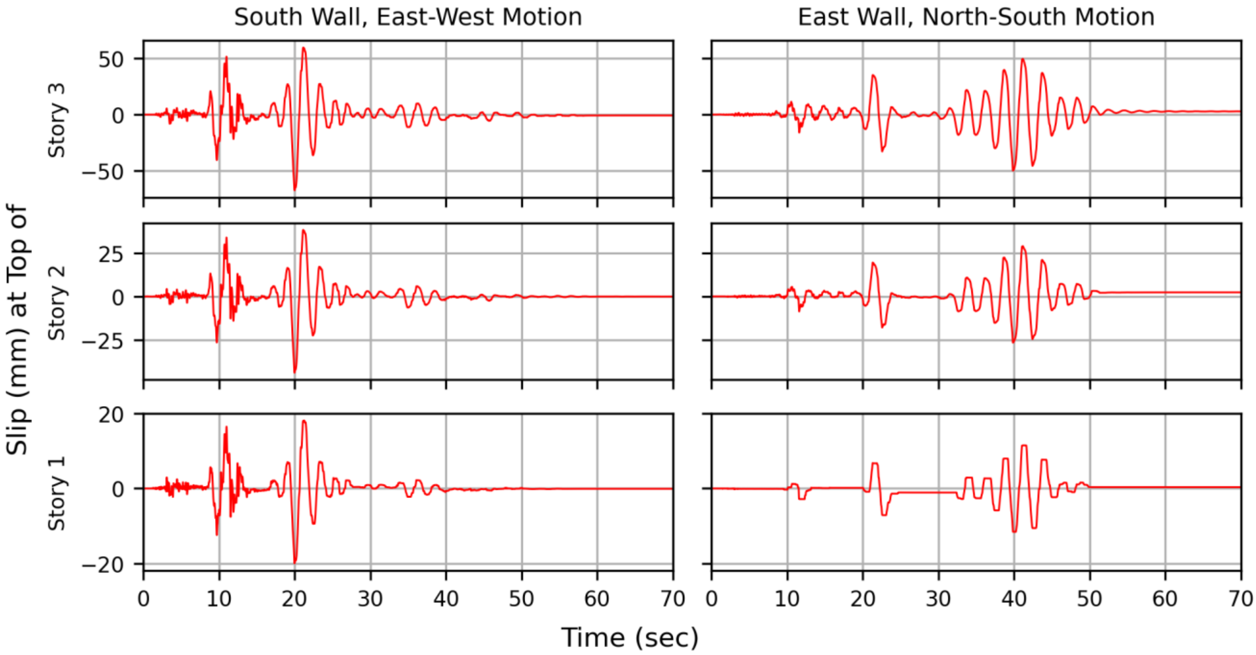

Figure 10: Representative time history of slip between wall and building floor for 475 Chi-Chi XY

5.2. Reduction in Drift

Figure 11 compares the peak interstory drift in the building to the percent reduction in peak subassembly interstory drift, calculated as the difference between building and subassembly maximum story interstory drift divided by maximum building interstory drift, across the testing program. The first 29 tests are excluded due to data synchronization issues. Interstory drift in the subassembly was consistently less than building interstory drift.

The 43-year ground motions saw little reduction in interstory drifts, despite building interstory drifts being nonzero. The slip mechanism does not activate at all for small earthquakes (Fig. 12). If the shaking intensity is not large enough to overcome friction and dislodge the clips from the U-strut, meaningful slip does not occur. However, as more intense earthquakes produced larger building interstory drifts, the walls experienced proportionally less interstory drift compared to the building as the amplitude of slip increases.

A trend between peak building interstory drift and drift reduction is visible. As building interstory drift increased, drift reduction also increased, indicating that the slip/drift joint plays a greater role in large earthquakes than small ones. This could be a desirable feature: the low building interstory drifts of frequent, smaller earthquakes do not cause damage, so the slip response is not needed. However, the increase in interstory drift reduction as demand interstory drift increases shows that the slip mechanism does activate in response to the larger interstory drifts that do cause damage that occur during more intense ground motions.

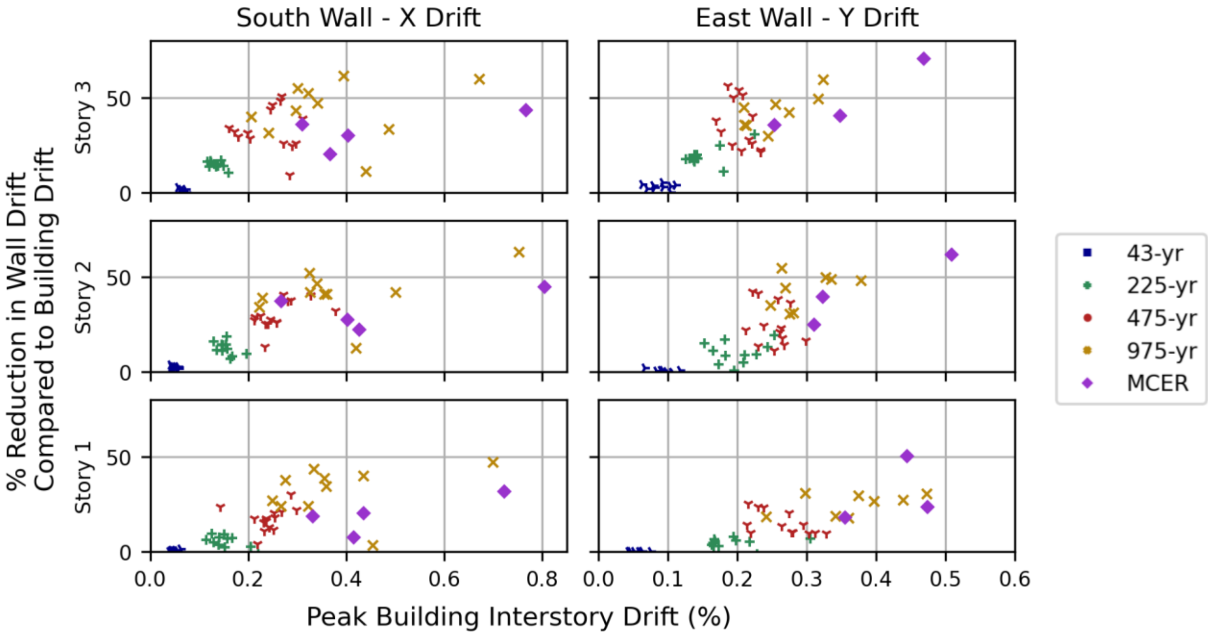

Figure 11: Percent reduction in nonstructural wall interstory drift compared to building interstory drift. Only tests with excitation in the direction of the plane of the wall are included.

Interstory drift reduction does not increase as markedly at the higher shaking intensities. This leveling out effect could be attributed to the fact that the exterior façade wall was isolated from the building drift, not the ground motion itself. A larger ground motion still increases the drift of the subassembly. This effect may also be an artifact of normalizing these reductions to the building interstory drift. A 20% reduction in interstory drift for a MCE_R earthquake is still larger than a 20% reduction for an equivalent 475-year earthquake.

Conversely, slip between the wall and building (Fig. 12) continues to increase as interstory drift increases without an apparent upper limit. This experiment did not identify a limit on the amount of slip the sliding clip system is able to accommodate. However, the increase in slip does not counteract all building motion, so the system could reach a limit state when the interstory drift in the subassembly is enough to cause damage to wall sheathing and framing.

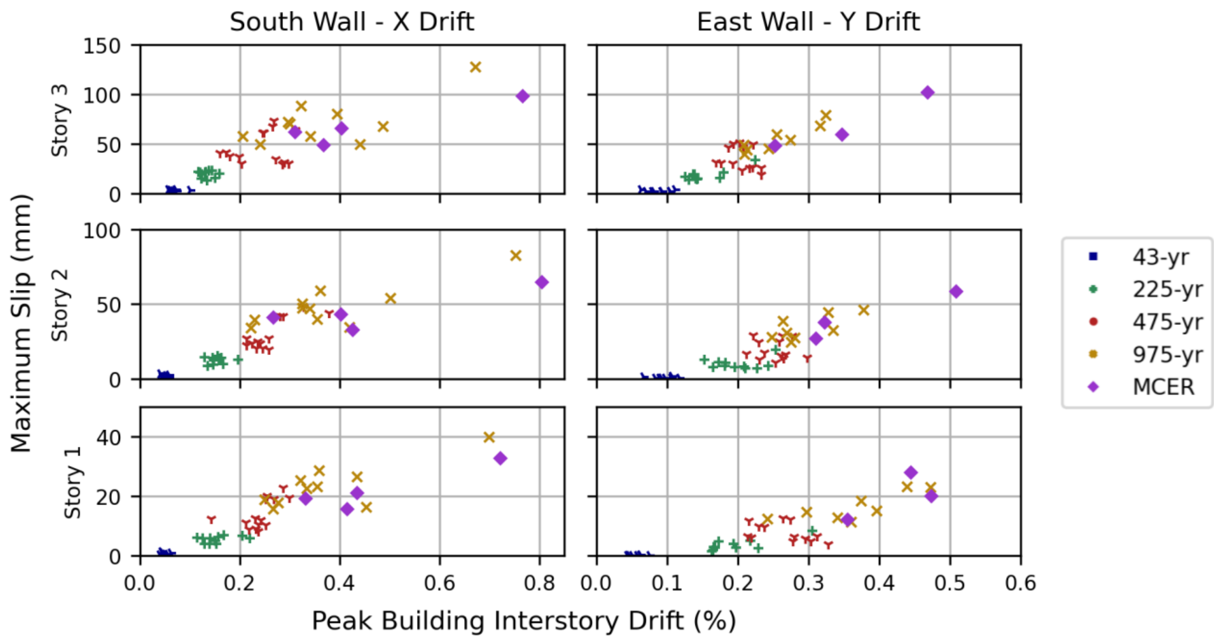

Figure 12: Absolute peak building interstory drift vs maximum slip

5.3. Residual Slip

One issue that arises when using a subassembly that slips relative to the building is whether the subassembly re-centers after excitation. Residual slips negatively impact aesthetics and could stress sealant across the movement joints. The drift clips exhibited stick-slip behavior, which prevented the subassembly from fully returning to its original position; however, these residual slips were small for most tests. Table 3 shows the maximum residual slips for each wall and level. Residual slips also accumulated over time, so the maximum cumulative residual slip of the subassembly was greater than the maximum residual slip of a single test.

Table 3: Maximum residual slips, single test and cumulative

Top of Story	Max. Residual Slip Across All Tests, mm (in.) South Side	East Side	Max. Change from Original Position, mm (in.) South Side	East Side
3	9.7 (0.38)	3.9 (0.15)	22.3 (0.88)	10.3 (0.41)
2	6.8 (0.27)	2.9 (0.12)	11.7 (0.46)	10.5 (0.41)
1	3.7 (0.15)	3.7 (0.08)	7.0 (0.27)	4.7 (0.19)

The three stories tended to have residual slips in the same direction and proportional in magnitude, with residual slips being larger for the higher levels. When the largest cumulative residual occurred, residual interstory drift in the wall was 0.3% assuming there was no residual interstory drift in the structure.

6. Conclusions

A three story balloon-framed exterior façade subassembly with sliding clips was incorporated as part of a full-scale building shake table test program that included 88 earthquake tests, 42 of which were design level or larger. Key findings include:

- Drift clips significantly reduced the amount of interstory drift passed to the façade. Because CFS-framed walls are drift-sensitive components, this reduction is key for reducing wall damage and promoting post-earthquake return to building functionality.
- Despite the sliding action, façade response was not fully decoupled from building response as some clips tend to bind within the U-strut, imposing drift demand from the building on the wall. This ensured that the façade did not oscillate out of phase with the building but also passed forces to the attachment clips, causing them to be the primary location of damage during the experiment. Binding in the U-track resulted in screw pull-out.
- Significant damage occurred where clips were not correctly installed.
- Following clip reinforcement, the system survived an additional 51 earthquakes, meeting the resilience objective. Reinforcing the clips delayed clip pull-out, but over the course of many earthquakes, clips that experienced binding without detaching from studs instead passed damage to the framing studs, causing stud bending and buckling. Assuming the system has sufficient redundancy, clip pull-out may be desirable over damage to framing members.
- Nevertheless, despite the building being subjected to a far higher number of earthquakes than would realistically ever occur, damage at the clips did not cause a life safety hazard, and the lack of damage to the sheathing, cladding, and windows is encouraging evidence that using drift clips improves façade performance by reducing damage to other components.
- Future projects may prevent pull-out by using thicker or higher yield strength studs, multiple clips per stud, or more screws per clip to increase pull-out resistance while also strengthening the system against other failure modes.
- Corner damage is a common issue for all exterior façade walls, especially for walls designed to slip relative to the building, but corner damage to the exterior façade walls in this experiment was avoided altogether by using an expansion joint cover capable of accommodating the expected amount of in-plane and out of plane movement.

7. Acknowledgements

The first author of this paper is supported by the NSF Graduate Research Fellowship under Grant No. 1937966. The structural system scope of NHERI TallWood Project is sponsored by NSF Grants No. 1635227, 1634628, 1634204. The use and operation of NHERI shake table facility is supported by NSF through Grant No.1520904. The nonstructural component scope of this project is sponsored by NSF Grant No. CMMI-1635363, USFS Grant No. 19-DG-11046000-16, Softwood Lumber Board, Computers and Structures Inc, the GAANN Fellowship Program at UNR, and industry sponsors. Materials and in-kind support for the wall subassemblies discussed in this paper are provided by CEMCO® Steel, Construction Specialties, Ehmcke Sheet Metal, Innotech Window and Door, Simpson Strong-Tie, Winco Window and USG. The subassembly was framed and sheathed by apprentices through the Southwest Carpenters Union Training Fund, and the windows and exterior panels were installed by Ehmcke Sheet Metal through partial donation. The authors are indebted to the many contributors that made this project possible. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

8. References

Daudet L.R. (2021). *Drift track*. US Patent No. US-10961704-B2.

Di Lorenzo G., De Martino A. (2019). “Earthquake response of cold-formed steel-based building systems: an overview of the current state of the art”, *Buildings*, 9(11): 228.

Fiorino L., Bucciero B., Landolfo R. (2019). “Evaluation of seismic dynamic behaviour of drywall partitions, façades and ceilings through shake table testing”, Engineering Structures, 180: 103-123.

Fischer E.C., Stringer M., Horiuchi C. (2017). “What structural engineers need to know about resilience”, Structure Magazine, January.

Pantoli E., Michelle C.C., Wang X., Astroza R., Ebrahimian H., Hutchinson T.C., Conte J.P., Restrepo J.I., Marin C., Walsh K.D., Bachman R.E., Hoehler M.S., Englekirk R., Faghihi M. (2016). “Full-Scale Structural and Nonstructural Building System Performance during Earthquakes: Part II – NCS Damage States”, *Earthquake Spectra*, 32(2): 771–794.

Pei S., van de Lindt J.W., Barbosa AR., Berman J.W., McDonnel E., Dolan J.D., Blomgren H.E., Zimmerman R.B., Huang D., Wichman S. (2019). “Experimental seismic response of a resilient 2-story mass-timber building with post-tensioned rocking walls”, Journal of Structural Engineering, 145(11): 04019120.

Pei S., Ryan K.L., Berman J.W., van de Lindt J.W. et al. (2023). “Shake table test of a full-scale ten-story resilient mass timber building”, Submitted to *Journal of Structural Engineering*.

Simpson Strong-Tie. (2023). *Connectors for Cold-Formed Steel Construction*. C-CF-2023. Simpson Strong-Tie, p.69. Available from: www.strongtie.com/resources/literature/cold-formed-steel-catalog.

Taghavi S., Miranda E. (2003). *Response assessment of nonstructural building elements*, PEER Report 2003/05, Pacific Engineering Research Center, University of California Berkeley.

Wichman S. (2023). *Seismic Behavior of Tall Rocking Mass Timber Walls*. Ph.D. Thesis, University of Washington, Seattle.

Zhou Y., Li R., Lu X.L. (2012). “Earthquake-resilient tall buildings using rocking walls”, Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal.