

Evaluation of Non-structural Walls with Drift-Compatible Details in a 10-Story Mass Timber Building Shake Table Test

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Abstract. Mass timber is a sustainable option for building design compared to traditional steel and concrete building systems. A shake table test of a full-scale 10-story mass timber building with post-tensioned mass timber rocking walls will be conducted as part of the NHERI TallWood project. The rocking wall system is inherently flexible and is expected to sustain large interstory drifts. Thus, the building's vertically oriented non-structural components, which include cold-formed steel (CFS) framed exterior skin subassemblies that use platform, bypass, and spandrel framing, a stick-built glass curtain wall subassembly with mechanically captured glazing, and CFS framed interior walls, will be built with a variety of innovative details to accommodate the large drift demands.

This paper will describe these innovative details and the mechanisms by which they mitigate damage, provide an overview of the shake table test protocol, and present performance predictions for the non-structural walls.

Keywords: non-structural walls, cold formed steel framing, drift-compatible details, shake table testing.

1. INTRODUCTION

Mass timber is a potentially more sustainable alternative to traditional concrete and steel construction. To make mass timber construction more viable for tall buildings, the NHERI TallWood project is underway at the outdoor shake table facility at the University of California, San Diego. A 10-story mass timber building will be erected on the shake table and subjected to ground motions of increasing intensity. This test building will employ mass timber rocking walls as its primary lateral force resisting system. Mass timber rocking walls can sustain large interstory drifts without damage [Hasani and Ryan, 2021], so it is desirable to provide and validate detailing options for non-structural systems that can likewise sustain large drifts without damage.

Non-structural walls, being interstory components, are particularly susceptible to damage from interstory drift. Furthermore, they often suffer extensive damage during earthquakes, causing significant economic loss and threats to human safety [Di Lorenzo and De Martino, 2019]. To mitigate drift-induced damage, the four exterior subassemblies used in this test will incorporate drift-compatible details designed to reduce or limit damage. Three subassemblies will use cold-formed steel (CFS) framing and use horizontal joints to accommodate relative horizontal movement between floors. The fourth subassembly, a stick-built curtain wall, accommodates drift through racking of the framing members and rotation of the glass within the frame. This paper describes these subassemblies and predicts their performance based on expected drift demands.

2. Project Description

2.1 DESCRIPTION OF MASS-TIMBER BUILDING TEST SPECIMEN

The test specimen will be built at the large-scale outdoor shake table facility at the University of California, San Diego. The 10-story test specimen, displayed in Figure 1, will be the world's tallest full-scale mass timber building ever tested. The test building will utilize a variety of mass timber products for the floor, gravity frame, and rocking wall components. Post-tensioned mass timber rocking walls, made of cross-laminated timber (CLT) and mass plywood panels (MPP), serve as the lateral force resisting systems in the building in the east-west and north-south directions, respectively. U-shaped flexural plates (UFPs) connected between the rocking wall and the bounding columns dissipate energy. The building's gravity framing consists of laminated veneer lumber (LVL) beams and columns detailed with pinned connections. Several types of mass timber components are utilized for floor diaphragms including CLT, veneer-laminated timber (VLT), glue-laminated timber (GLT), nail-laminated timber (NLT), and dowel-laminated timber (DLT).

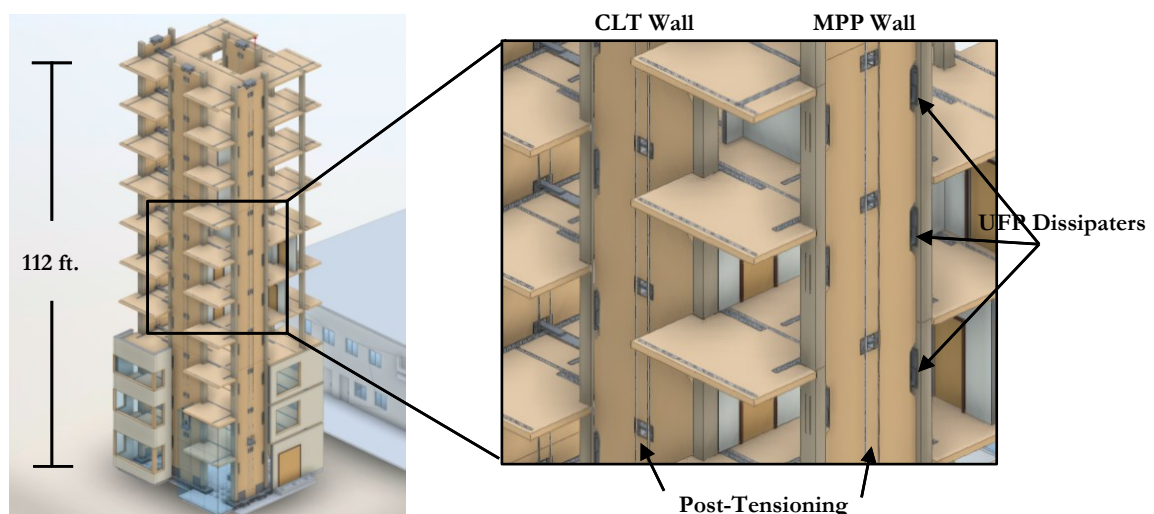


Figure 1. 10-Story Testbed Structure

2.2 DESCRIPTION OF SUBASSEMBLIES

The testbed structure will have four non-structural exterior wall subassemblies. Three of these are CFS framed systems and the fourth is a stick-built curtain wall. Each of these subassemblies employs innovative details to mitigate drift-induced damage. All of the subassemblies have windows, which vary in size and aspect ratio.

2.2.1 Subassembly 1: Platform-Framed CFS Exterior Wall

The first subassembly (Figure 2a) is L-shaped and uses platform framing, wherein studs bear directly on the floor below and are connected to the floor above via an inverted “header” track. Drift is accommodated using a joint at the header track. The first and third stories use double (nested) slip tracks (Figure 2b) where slip occurs between a header track connected to the floor above and a lower header track connected to the wall studs and sheathing. For comparison, the second floor uses CEMCO’s CST Brand Slotted Slip-Track (Figure 2c). Slotted slip tracks are attached directly to the floor above and slip occurs between the header and floor due to slotted holes for fasteners. Slotted slip tracks are easier to install and require less material than double slip track assemblies; however, the slip mechanism needs to be verified through experimental testing.

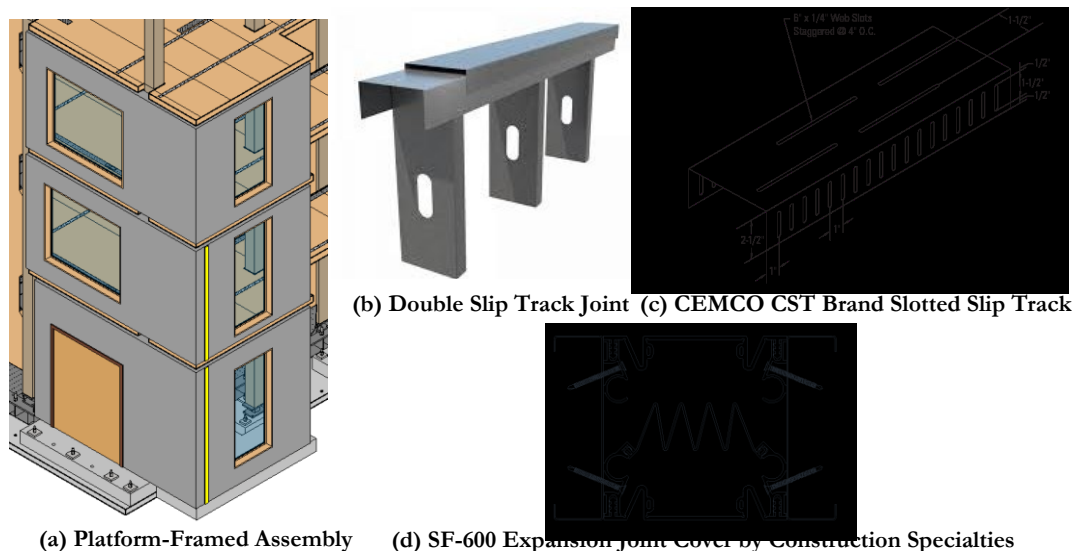


Figure 2. Platform-framed CFS subassembly (a) and drift-compatible details (b-d)

Research has shown that damage is prevented when interior CFS partition walls, which are constructed similarly to platform-framed walls, are constructed with double slip tracks; however, increased damage occurs at wall intersections [Hasani and Ryan, 2021]. To address the drift incompatibility at the corners, the first and second stories will use SF-600 expansion joint covers supplied by Construction Specialties (Figure 2d), which are intended to separate the movement of adjoining walls. The vertical expansion joints provide 4 in. relative movement between adjoining perpendicular walls in both directions. The third story serves as a control specimen and lacks an expansion joint. However, the interior framing layout at the corner was designed to be more flexible than typical construction, which should delay or reduce the severity of damage. The corner of the third story could suffer significant damage while the other two stories should accommodate in-plane drift without significant damage.

2.2.2 Subassembly 2: Bypass-Framed CFS Exterior Wall

The second subassembly (Figure 3a) is an L-shaped subassembly with bypass framing, wherein long studs span multiple stories outside of the diaphragm envelope. Damage in bypass-framed walls is typically

concentrated at the clips used to attach studs to the structural system [e.g. Wang *et al.*, 2015; Schafer *et al.*, 2016]. Therefore, drift can be accommodated by connecting the studs to the floor diaphragm via a clip that is free to slide laterally. This will be accomplished using a DSSCB clip from Simpson Strong-Tie installed into standard U-track (Figure 3b). This connection resists out-of-plane loads while permitting in-plane movement of the clip within the U-track.

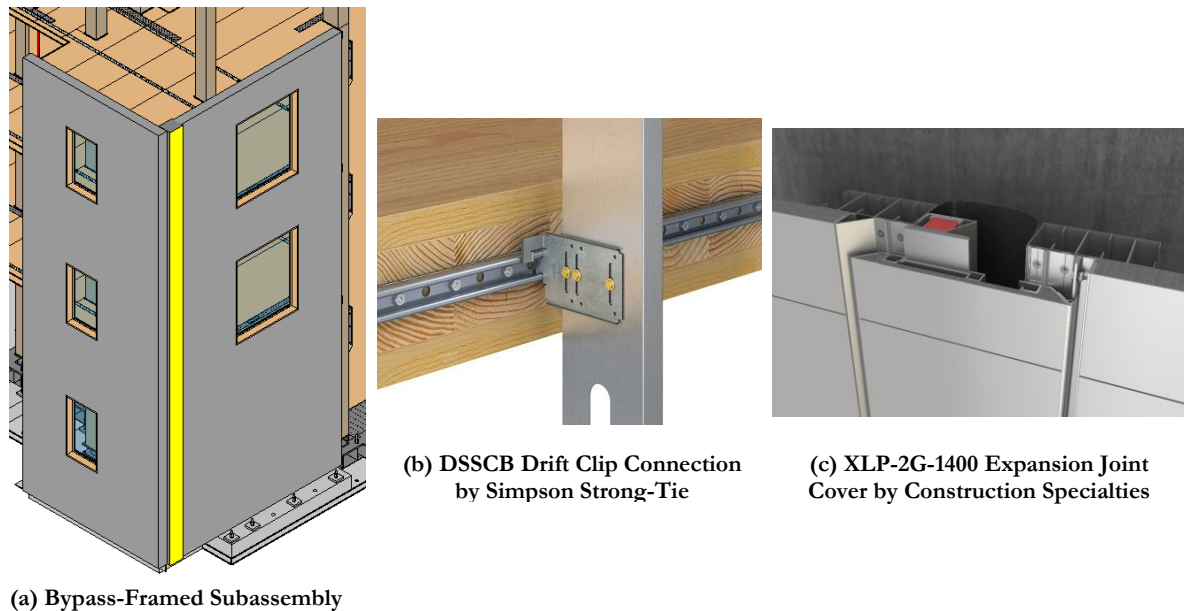


Figure 3. Bypass-Framed CFS Subassembly and Details

Because this subassembly is continuous over three stories, interstory drifts accumulate over multiple floors and a relatively large gap is needed to separate adjacent walls. This gap is covered by an XLP-2G-1400 expansion joint cover supplied by Construction Specialties, a 14 in. cover with vertical hinges to allow it to open and close when the walls move relative to one another (Figure 3a and 3c). Magnets keep the cover closed under normal operation and reset the assembly after shaking. This joint is sized to allow an average of 2.3% drift in each direction over the height of the wall.

Without means to transfer in-plane forces to the structure, inertial forces are collected over the entire height of the subassembly, so special attention is required for shear design, especially given the high height to width ratio of the walls. The subassembly was designed as a shear wall and uses large holdowns at the ends of each wall and CEMCO Sure-Board® for enhanced shear strength.

2.2.3 Subassembly 3: Spandrel-Framed CFS Exterior Wall

The third subassembly, which uses spandrel framing, is C-shaped with two corners (Figure 4a). Spandrel framing consists of bands of short studs rigidly to a floor diaphragm via rigid metal clips (Figure 4c) and kicker studs (Figure 4b). Loads from the spandrel are transferred directly to the diaphragm to which it is attached. The space between spandrels can be filled with windows or infill studs. Drift compatibility is achieved by placing a double slip track (Figure 2b) between the window and the spandrel above. At the base of the wall, the lowest spandrel cannot use a kicker stud, so it is instead anchored to the foundation using a moment-resisting connection (Figure 4d).

Spandrel framing is often used so that a “ribbon” of windows can extend around the entirety of the structure without interruption. Thus, the windows in this subassembly wrap around its corners (Figure 4a) for aesthetic appeal. This will demonstrate whether typical window framing is flexible enough to permit

perpendicular wall motion without damage. For comparison, the second floor instead incorporates a SF-600 joint between perpendicular windows to fully separate their movement (Figure 2d, 4a).

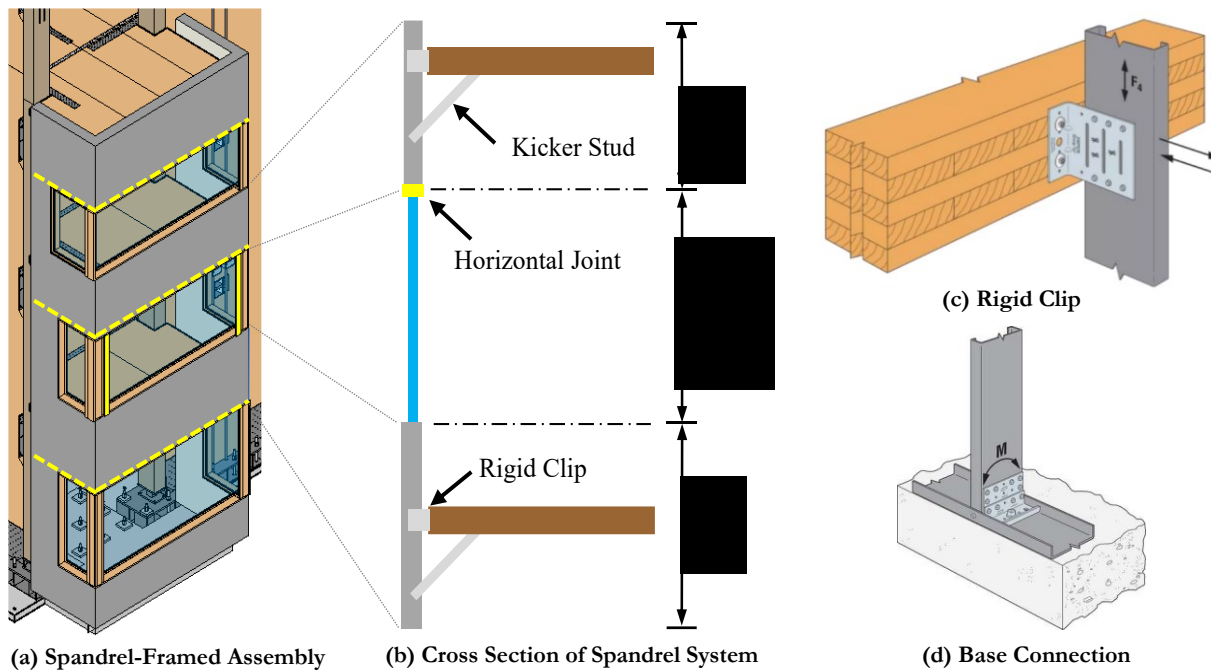


Figure 4. Spandrel-Framed Subassembly and Details

2.2.4 Subassembly 4: Stick-Built Curtain Wall

The fourth subassembly is a C-shaped curtain wall that spans the first two stories of the building and utilizes 1-1/16" 60-minute fire-rated glazing. The framing consists of heavy fire-rated S235JR steel horizontal and vertical mullions that support the glass lites. The subassembly is secured to the foundation and the edges of the 2nd and 3rd floor diaphragms of the building. To accommodate drift during seismic loading, the curtain wall system utilizes a stick-built system in which the framing racks (or distorts) to displace with the floor diaphragms. Because the curtain wall is C-shaped, the subassembly also utilizes a soft corner detail with a fire-rated fill to allow for independent movement of the perpendicular wall sections.

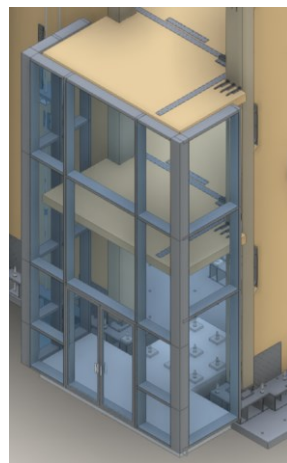


Figure 5. Curtain Wall with Stick-Built Framing

The glass panels in the curtain wall system are held in place using mechanically captured glazing, which consists of gasketed pressure plates mechanically secured to the mullions through the glazing pocket to hold

the glass in place. The panels are designed to rotate within the frame and avoid frame-to-glass contact, which causes concentrated stresses at the corners of the panels and lead to crushing of the glass. The curtain wall system must satisfy the provisions of ASCE 7-16 Section 13.5.9 to prevent glass fallout at the peak drift, in which the glass fallout displacement is determined in accordance with AAMA 501.6 or by engineering analysis.

2.3 DESCRIPTION OF MODEL

A model of the structural system was developed in OpenSees by Wichman *et al.* [2022b] for performing non-linear response history analyses for the design of the lateral-force resisting system. The performance of the non-structural walls is estimated herein by comparing the interstory drift demands computed by the Wichman *et al.* [2022b] model to the respective drift capacities of each subassembly.

Figure 6 shows details of the numerical model of the building specimen. As shown in Figure 6e, the model includes the four structural rocking walls with their boundary columns and a rigid diaphragm constraint at all floors. Figure 6a shows a detailed schematic of the typical structural wall modelling methodology, based on techniques similar to those presented in Wichman *et al.* [2022a]. The post-tensioning (PT) bars were modelled using corotational truss elements with a bi-linear tension-only material model that accumulates damage after yielding (Figure 6b). The initial post-tensioning of the walls was modelled by applying an initial strain wrapper to the PT truss elements. At each story, the UFPs were modelled using zero-length spring elements with the uniaxial Giuffre-Menegotto-Pinto steel material model shown in Figure 6c.

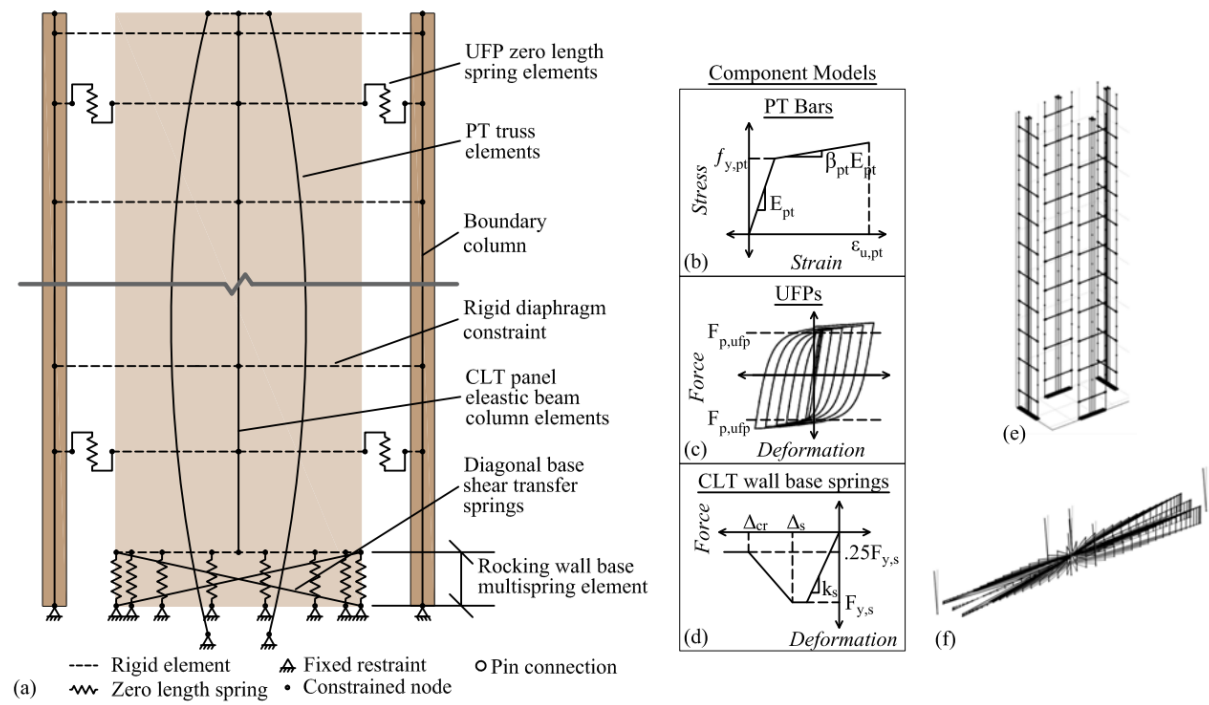


Figure 6. Numerical model schematic and material models used to model the 10-story building [Wichman *et al.*, 2022b]

To model the mass timber wall panels, a series of elastic beam-column frame elements were used. These elements included axial, flexural, and shear deformations. The inelastic compressive deformation at the base of the walls was modelled using a multispring contact element, initially developed by Spieth *et al.* [2004]. In this element, zero-length springs are distributed in parallel along the length and width of the wall base such that in-plane and out-of-plane rocking can be modelled. Figure 6f shows an isotropic view of these springs while the wall is rocking. The top of each spring is rigidly connected to the base of the wall and each spring uses the compression-only hysteretic material model shown in Figure 6d.

2.4 TESTING PROTOCOL

The specimen was designed to meet seismic demands computed per ASCE 7-16 for a location in Seattle, Washington with a Class C soil site. For design and test planning, suites of eleven 3D ground motions were selected and scaled to five hazard levels. The hazard levels included four return periods (43-year, 225-year, 475-year, and 975-year) and a risk-targeted maximum considered earthquake (MCE_R), all defined and scaled in accordance with ground motion scaling procedures outline in ASCE 7-16. From the original suites of eleven ground motions, five records, representative of suite mean behaviour, were selected at each hazard level for shake table preconditioning. The results presented here are for those five ground motion records. While the exact motions and sequencing will be adjusted as the test program progresses, they will likely be selected from the sets of five motions presented here.

As test planning is ongoing at the time of writing, only high-level details of the TallWood team's preliminary test plan are presented here, with the understanding that adjustments may be needed based on real time observations. First, about six weeks is planned for testing, and two trials (shakes) can be executed per day allowing adequate time for inspection and recharging the shake table after shutting down. Second, several trials at each of the hazard levels are desired. The intention behind repeating trials at a given hazard level is to develop fragilities for various structural and non-structural elements, albeit recognizing the limitations of having only a single specimen for most of the unique details. Trials will include motions applied in X-direction (east-west), Y-direction (north-south), bidirectionally (XY) and tridirectionally (XYZ). Note, results presented in this paper are all bidirectional application of the five records for each hazard level. Caution will be applied when executing vertical motions based on understanding of the sensitivity of non-structural elements to vertical shaking along with the desire to initially isolate the effect of the lateral motion for each intensity level; thus, vertical shaking is not considered in this analysis.

3. Damage Predictions

The model produced a time history of the displacements of the centerlines of each rocking wall, which were then used to calculate rigid body motion of the diaphragm at each floor level and the peak drift demands for the exterior wall subassemblies at each corner of the building. The interstory drift demands are shown in Figure 7 with horizontal lines indicating the drifts where the onset of damage is expected in each subassembly. These drifts and a description of expected damage are given in Table 1.

Peak building interstory drift ratios remain under 1.75% in the east-west direction, where the CLT walls resist lateral loads, and 2.25% in the north-south direction, parallel to the MPP walls. This difference in drift demands is due to minor differences in the CLT and MPP lateral force resisting systems, eccentricities in mass distribution, and relative magnitudes of the input earthquake motions in the two orthogonal directions.

3.1 SUBASSEMBLY 1: PLATFORM-FRAMED CFS EXTERIOR WALL

The first subassembly is expected to remain relatively undamaged on the first two floors. The vertical joint provides 2.5% interstory drift before onset of damage, above the maximum drift predicted by any of the simulations (2.25%, north-south MCE_R ground motions in Figure 7). Should drift exceed 2.5%, sheathing crushing and fastener tearing are the first types of damage that would be expected.

The third floor does not use a corner joint and its damage can be better predicted by previous research. Davies *et al.* [2011] showed that walls with friction connections (a close analogue to slip track walls) and perpendicular walls start suffering damage at 0.59% drift; however, this damage is limited to sheathing separation at the wall intersection and localized crushing of the gypsum sheathing. This limit is shown by the lowest horizontal line in Figure 7e and 7f. This limit may be exceeded by some 225-year ground motions and is certain to be exceeded at ground motions with longer recurrence intervals.

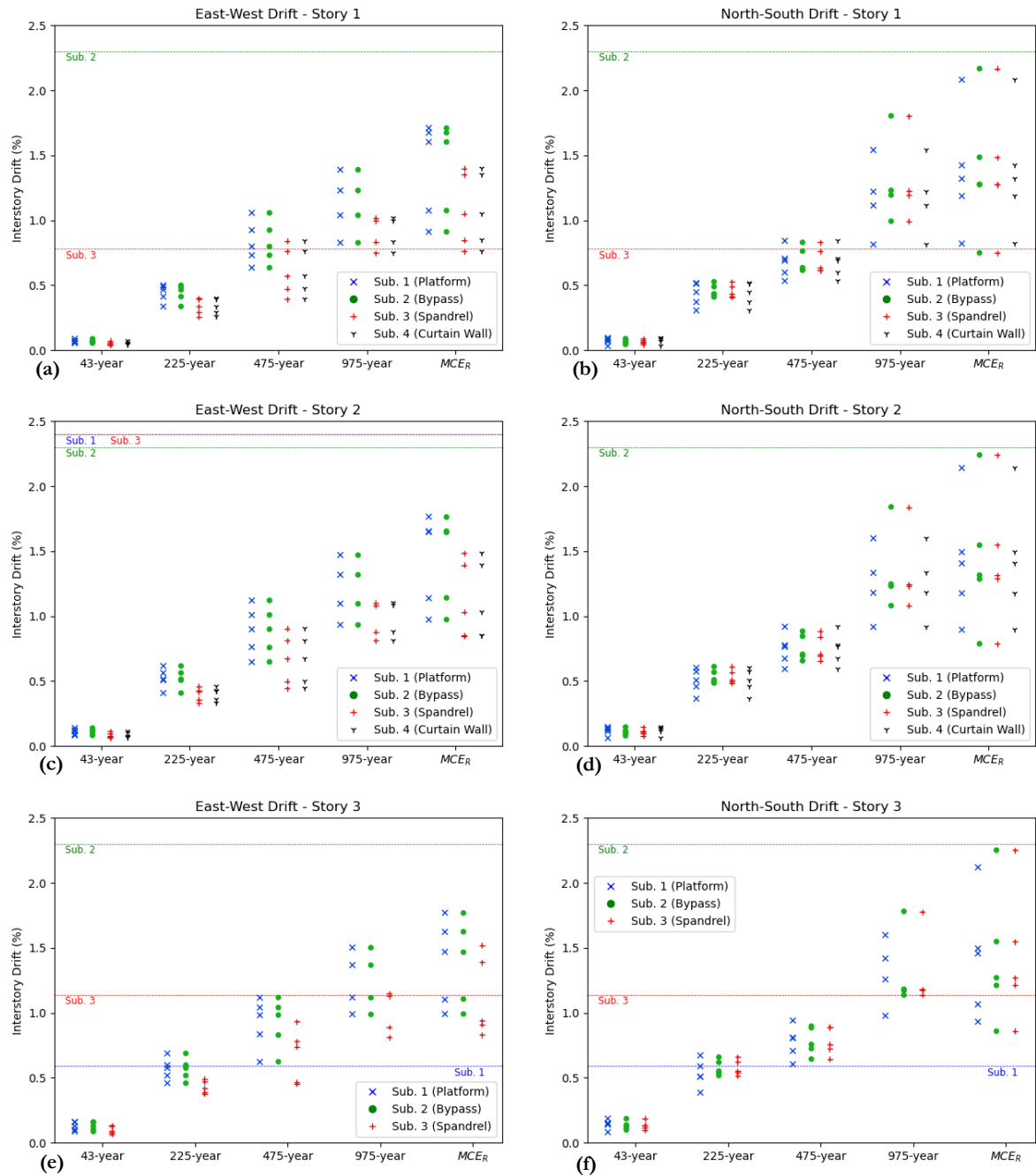


Figure 7. Building peak interstory drift demands and damage limits

Two design improvements may increase the drift limit of the third floor compared to previous research on platform framed CFS walls. Davies *et al.* [2011] suggested that gypsum crushing may be reduced by providing a small vertical gap between the gypsum and upper floor. This subassembly incorporates such a gap and will show whether it reduces damage or delays its onset. To further lessen damage at the corner, the CFS framing was designed to be flexible at the corner by using few studs and not connecting them to one another.

The slotted slip track on the second floor has a hard limit on its in-plane drift capacity, whereas the double slip track assemblies do not. The limited length of the slots in the header track will cause damage to the screws and track at drifts greater than 2.4%. However, the slotted slip track may be advantageous compared

to double slip tracks under extreme out-of-plane drifts where a double slip track wall may unseat and fall over while a slotted slip track would be held in place, preventing a component collapse threat.

Table 1. Summary of damage predictions

Subassembly	% Drift at Onset of Damage	Expected Damage
Sub. 1 – Floor 1	2.5%	No damage under any hazard level.
Sub. 1 – Floor 2	2.4%	No damage under any hazard level.
Sub. 1 – Floor 3	0.59%	Damage possible for 225-year and damage expected more severe earthquakes.
Sub. 2 – All Floors	2.3%	No damage under any hazard level.
Sub. 3 – Floor 1	0.78%	Minor damage to window framing under 475-year earthquake. Window cracking and framing distortion expected under 975-year and MCE_R .
Sub. 3 – Floor 2	3.00%	No damage under any hazard level.
Sub. 3 – Floor 3	1.14%	Window framing damage under 225-year earthquake and cracking under more severe hazard levels.
Sub. 4 – Floor 1	2.50% EW	Damage in the north-south direction possible only at MCE_R . No glass fallout expected.
	3.05% NS	
Sub. 4 – Floor 2	2.50% EW	
	3.42% NS	

3.2 SUBASSEMBLY 2: BYPASS-FRAMED CFS EXTERIOR WALL

The drift limit for this subassembly is based on the XLP-2G-1400 joint cover capacity and represents an average drift over the height of the three-story assembly (i.e., the limit can be locally exceeded on one floor as long as the total is not exceeded.) As can be seen in Figure 7, no ground motion has a predicted drift that exceeds this sub assembly's expected drift at damage initiation. Thus, the bypass-framed subassembly is expected to remain undamaged under most hazard levels. One MCE_R does near this wall's drift limit in the north-south direction (Figure 7d and 7f), so there is very little conservatism in the design. However, the three-story subassembly is isolated from the building's motion in the in-plane direction, so the building's motion may be a poor predictor of the wall's response. The subassembly may respond to the ground motion according to its own dynamic properties, potentially resulting in larger drifts than predicted here.

A previous test with bypass framed CFS walls with slotted clips by Wang *et al.* [2015] showed that damage usually commences with deformation of the clips. However, the drift clips used in this experiment are specifically designed to avoid this kind of damage, so damage is instead expected to be redirected to the wall end zones, namely via sheathing cracking and end stud distortion.

3.3 SUBASSEMBLY 3: SPANDREL-FRAMED CFS EXTERIOR WALL

The vertical joint covers on the second story of the platform-framed subassembly provide sufficient drift capacity to avoid damage under the selected suite of ground motions (Figure 7c and d). However, due to framing limitations, the exterior sheathing may interfere with the slip track assembly's motion on all three stories. Depending on final, as-built details, this may cause some limited damage to the corners of the exterior sheathing on the north side of the subassembly; however, this damage should remain localized.

Conversely, the first and third stories have no mechanism to accommodate corner drift incompatibility other than the inherent flexibility of the windows themselves. The windows are designed to be somewhat flexible, and their drift capacities were estimated by performing a detailed examination of construction

drawings. Figure 7a-b shows that damage may occur at the third story during 475-year earthquakes, and Figure 7e-f shows that damage may occur in the east-west direction and is very likely to occur in the north-south direction during the 975-year earthquakes. Window frame distortion and glass cracking are likely to be the first types of damage this subassembly experiences.

3.4 SUBASSEMBLY 4: STICK-BUILT CURTAIN WALL

The drift that corresponds to the onset of damage in curtain walls can be taken as a function of the aspect ratio of a window and the clear space between the glass lite and surrounding framing. A window's drift capacity increases as its aspect ratio increases [Memari *et al.*, 2011]. The drift limits shown in Table 1 represent the drift limits at which the window with the smallest aspect ratio reaches its drift capacity. Framing yielding and minor glass cracking occur when this drift limit is exceeded [Memari *et al.*, 2007]. No damage is expected; these drift limits fall just outside of the range shown in Figure 7.

If the drift limit of the curtain wall is exceeded too far, glass shatter or fallout may occur, which is particularly dangerous and undesirable. Fallout may be assumed to occur when the design drift is exceeded by 25% [Memari *et al.*, 2007, 2011]. While the curtain wall's drift limit is somewhat close to drifts imposed by certain MCE_R ground motions, sufficient excess capacity is provided to minimize risk of glass fallout.

4. Conclusions

The upcoming NHERI TallWood 10-story shake table test will include four non-structural, exterior wall subassemblies. The subassemblies are designed to accommodate interstory drift, and certain walls are designed to overcome drift incompatibilities at wall corners. This paper correlates predicted peak interstory drift to drift limit states of the non-structural walls to identify when damage is likely to occur. The CFS-framed walls which use vertical joints to avoid corner damage will remain undamaged under all but the most extreme hazard levels whereas CFS wall construction that incorporates drift-compatible detailing for in-plane motions but does not account for drift incompatibilities at wall corners is expected to avoid damage at most service-level earthquakes, but significant corner damage may occur at design-level earthquakes.

4.1 FUTURE WORK

At the time of writing, construction of the test building is underway. Shake table testing is expected to commence in January 2023. The upcoming test will verify whether or not these details successfully mitigate non-structural wall damage due to interstory drift. Physical testing is essential because the subassemblies incorporate new details that have not yet been studied in publicly available seismic testing programs. The seismic behaviour of these walls, which use novel details, may be far different from the more typical construction used in the references cited in this paper.

For instance, a key question is whether the subassemblies will suffer damage due to the vertical deflection of the diaphragms. The CFS-framed exterior wall subassemblies were generally designed to allow 0.75 in. vertical deflection. The model used in this study does not account for diaphragm rigidity, so physical testing is needed.

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