PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Cripple Wall Small-Component Test Program: Comparisons

A Report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project

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PEER Report 2020/19

Pacific Earthquake Engineering Research Center

Headquarters, University of California at Berkeley

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ABSTRACT

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled "*Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings*," henceforth referred to as the "PEER–CEA Project."

The overall objective of the PEER–CEA Project is to provide scientifically based information (e.g., testing, analysis, and resulting loss models) that measure and assess the effectiveness of seismic retrofit to reduce the risk of damage and associated losses (repair costs) of wood-frame houses with cripple wall and sill anchorage deficiencies as well as retrofitted conditions that address those deficiencies. Tasks that support and inform the loss-modeling effort are: (1) collecting and summarizing existing information and results of previous research on the performance of wood-frame houses; (2) identifying construction features to characterize alternative variants of wood-frame houses; (3) characterizing earthquake hazard and ground motions at representative sites in California; (4) developing cyclic loading protocols and conducting laboratory tests of cripple wall panels, wood-frame wall subassemblies, and sill anchorages to measure and document their response (strength and stiffness) under cyclic loading; and (5) the computer modeling, simulations, and the development of loss models as informed by a workshop with claims adjustors.

This report is a product of Working Group 4 (WG4): *Testing*, whose central focus was to experimentally investigate the seismic performance of retrofit and existing cripple walls. Amongst the body of reports from WG4, in the present report, a suite of four small cripple wall test phases, in total 28 specimens, are cross compared with varied exterior finishes, namely stucco (wet) and non-stucco (dry) exterior finishes. Details representative of era specific construction, specifically the most vulnerable pre-1960s construction are of predominant focus in the present effort. Experiments involved imposition of combined vertical loading and quasi-static reversed cyclic lateral load onto cripple walls of 12 ft in length and 2 ft or 6 ft in height. All specimens in this report were constructed with the same boundary conditions and tested with the same vertical load. Parameters addressed in this report include: wet exterior finishes (stucco over framing, stucco over horizontal lumber sheathing, and stucco over diagonal lumber sheathing); and dry exterior finishes (horizontal siding, horizontal siding over diagonal sheathing, and T1-11 wood structural panels) with attention towards cripple wall height and the retrofit condition. The present report provides only a brief overview of the test program and setup; whereas a series of three prior reports present results of test groupings nominally by exterior finish type (wet versus dry). As such, herein the focus is to cross compare key measurements and observations of the in-plane seismic behavior of all 28 specimens.

ACKNOWLEDGMENT AND DISCLAIMER

ACKNOWLEDGEMENT

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DISCLAIMER

This research study was funded by the California Earthquake Authority (CEA). The support of the CEA is gratefully acknowledged. The opinions, findings, conclusions, and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the CEA, Pacific Earthquake Engineering Research Center (PEER), project team members, or the Regents of the University of California.

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1.1 PREAMBLE

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled "*Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings*," henceforth referred to as the "PEER–CEA Project."

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Within the PEER-CEA Project, detailed work described above was conducted by seven Working Groups, each addressing a particular area of study and expertise, and collaborating with the other Working Groups. The seven Working Groups are as follows:

Working Group 1: Resources Review

Working Group 2: Index Buildings

Working Group 3: Ground Motion Selection & Loading Protocol

Working Group 4: Testing

Working Group 5: Analytical Modeling

Working Group 6: Interaction with Claims Adjustors and Catastrophe Modelers

Working Group 7: Reporting

This report is a product of the Working Group denoted in bolded text above.

Working Group 4: Testing focused on the first phase of an experimental investigation to study the seismic performance of existing[1] versus retrofitted cripple walls with sill anchorage. Amongst the body of reports prepared by Working Group 4 (WG4), the present report compares the response of a suite of four small cripple wall test phases for a total 28 specimens, with varied exterior finishes, namely stucco (wet) and non-stucco (dry) exterior finishes. Interested readers may refer to the report of Schiller et al. [2020(a)] for the strategy adopted to characterize the primary variables and their ranges within the small-component cripple wall test program conducted at the University of California San Diego (UC San Diego). In addition, the background and motivation for the study, field observations from past cripple wall failures, previous research on the topic, and details of how the loading protocol were selected are discussed [Schiller et al. 2020(a)]. Observations and results from all tests included in this experimental investigation were provided in the three previous reports [Schiller et al. 2020(a); 2020(b); 2020(c)]. It is noted that large-component tests were conducted within the scope of WG4; see Cobeen et al. [2020]. To this end, a comprehensive report comparing like-specimens from the small-component test program with those within the large-component test program is available; see Schiller et al. [2020(e)].

1.2 TEST PROGRAM AT UC SAN DIEGO

The small-component test program at UC San Diego was divided into four phases, with six to eight specimens tested per phase. Subdividing the program into multiple phases allowed analysis of one phase of test results to aid in the design of subsequent phases. In addition, this resulted in a manageable number of full-scale specimens within the laboratory space. Each of the test phases considered a similar theme, allowing for meaningful comparisons amongst specimens within a particular phase and yet were complimentary to other phases for cross comparison upon completion of subsequent phases. The scope and purpose of each testing phase is as follows:

- *Phase 1.* The first phase of testing considered six cripple wall specimens. Each of the cripple walls were 2 ft tall and finished on their exterior face with stucco installed over horizontal lumber sheathing. In addition, a uniform vertical load of 450 lbs/ft was applied to each specimen. Parameters amongst specimens in this phase included: the specimens boundary conditions, anchorage conditions, and existing versus retrofitted detailing. By controlling the exterior finish, height, and applied vertical load, the results of the Phase 1 tests work offered insight into the importance of the boundary conditions (ends, top, and bottom) of the wall on the performance of the specimens. In addition, one of the cripple walls was constructed with a wet set sill, a previously untested type of anchorage. Lastly, two of the cripple walls were identical, with one being an existing condition and the other being a retrofitted condition [Schiller et al. 2020(a)];

[1] An important note regarding terminology: For the present report series, cripple walls in their “as-built” configuration are referred to as either “existing”, “unretrofit”, or “unretrofitted” cripple walls, all terms being synonymous. In addition, the terms “retrofit” and “retrofitted” are both used interchangeably to describe cripple walls to which sill anchorage and bracing have been added. No other types of seismic retrofit are considered in this project, for instance chimney, roof, garage opening or porch attachment changes. Additional information on terminology and definitions related to this Project can be found in a glossary appendix of the WG 7 Project Technical Summary [Reis 2020].

- *Phase 2.* The second phase of testing contained eight cripple wall specimens. Six of the cripple walls were 2 ft tall, and two of the cripple walls were 6 ft tall. Similar to Phase 1, all wall specimens were subjected to 450 lbs/ft of vertical load. The boundary conditions remained the same for all specimens. The walls differed from each other in exterior finishes, height, and retrofit condition. The eight walls were grouped in four identical pairs of existing and retrofitted walls. All specimens had sill plates attached to the foundation with anchor bolts. The main focus of Phase 2 was to document the performance of dry, or non-stucco, exterior finish materials. One pair of walls was finished with T1-11 wood structural paneling, one pair was finished with shiplap horizontal lumber siding over diagonal lumber sheathing, and the final two pairs were finished with shiplap horizontal lumber siding. The two pairs with horizontal siding differed in height: 2-ft-tall versus 6-ft-tall cripple walls. These tests provided insight regarding the performance of dry finished specimens, with emphasis on understanding the failure mechanisms associated with short and tall cripple walls. In addition, the results of four retrofit walls built upon knowledge gained in Phase 1 regarding the effectiveness of the *FEMA P-1100* prescriptive retrofit [Schiller et al. 2020(b)];
- *Phase 3.* The third phase of testing also consisted of eight specimens. These specimens were each 2 ft tall and had the same boundary conditions imposed on the top and ends of the cripple walls. The three pairs of identical walls that only differed in their retrofitted condition. A uniform vertical load of 450 lbs/ft was consistently applied for all specimens. Key parameters differing among the specimens in this phase included the exterior finish details and the bottom of specimen boundary conditions. Testing considered pairs of cripple walls with stucco over horizontal lumber sheathing, stucco over diagonal lumber sheathing, and stucco over framing. One cripple wall was constructed with a wet set sill plate. Results of these three pairs of tests examined the performance of differing wet or stucco exterior finishes, as well as provide additional results regarding the performance of the *FEMA P-1100* prescriptive retrofit [Schiller et al. 2020(c)]; and
- *Phase 4.* The final phase of testing consisted of six specimens. All wall specimens were detailed with the same boundary conditions. Two pairs of identical 6-ft-tall cripple walls were tested, both existing and retrofit. Two walls were detailed with stucco over framing exterior finishes, while the other two utilized T1-11 wood structural panel exterior finishes. Two of the six specimens were 2 ft tall. One of these had stucco over horizontal lumber sheathing and was loaded with a monotonic push. The other cripple wall had shiplap horizontal sheathing over diagonal lumber sheathing and was tested with a light uniform vertical load of 150 lbs/ft. Results from this phase investigated the effect of height on the performance of the cripple wall and the *FEMA P-1100* prescriptive retrofit. In addition, the effect of a light vertical load and a monotonic push loading protocol was evaluated [Schiller et al. 2020(b); 2020(c)].

While there are four phases of testing, the reporting of each phase is not strictly organized based on the testing phase. Four reports document the UC San Diego small-component test program. Their organization is as follows. The first and third report focus on documenting the response of wet specimens, i.e. specimens with stucco exterior finishes, and boundary conditions (Phase 1). The second report focuses solely on dry specimens, i.e., specimens finished with wood absent stucco (Phase 2 and a portion of Phase 4). The present report (number 4) focuses on comparing the response of all specimens, wet and dry finished. Citations of these reports are as follows:

- Report 1: Cripple Wall (Small) Component Test Program: Wet Specimens I [Schiller et al. 2020(a)]
- Report 2: Cripple Wall (Small) Component Test Program: Dry Specimens [Schiller et al. 2020(b)]
- Report 3: Cripple Wall (Small) Component Test Program: Wet Specimens II [Schiller et al. 2020(c)]
- Report 4: Cripple Wall (Small) Component Test Program: Comparisons [Schiller et al. 2020(d)]

1.3 ORGANIZATION OF REPORT

The present, culminating report in the series of reports dedicated to the small-component test program, is organized as follows:

- Chapter 2 provides a recap of the entire test matrix and details of all specimens (Phases 1–4). Note these are provided in a condensed format as their details may be found in prior reports within this series. Likewise, a concise summary of the test setup and common instrumentation adopted throughout the entire program are included;
- Chapter 3 presents a cross-comparison of the key response features measured in these experiments. Notably strength, stiffness, and deformation capacity, as well as global load-deflection response from specimen groupings with similar general characteristics;
- Chapter 4 summarizes the extensive documentation of the physical damage to each cripple wall specimen collected during each test. This summary discusses the main features that varied across the four phases of testing, where damage modes were noted to be of significant impact on the behavior of the specimens. These damage features are linked to salient measured load-deflection response variations; and
- Finally, Chapter 5 provides concluding remarks regarding observations from the comparison of all phases of the small-component cripple wall test program.

2 Summary of Phases 1–4 Test Matrix, Setup, and Loading Protocol (Recap)

2.1 GENERAL

This chapter focuses on the details of the cripple wall specimens, test setup, and testing instrumentation for the entire UC San Diego testing program. Table 2.1 provides details of the complete testing matrix, delineated by phases. Overall, 28 cripple walls were tested: 17 specimens were finished with wet materials (stucco), and 11 specimens were finished with dry materials. The wet exterior finishes tested were as follows: (1) stucco over framing; (2) stucco over horizontal lumber sheathing; and (3) stucco over diagonal lumber sheathing. The dry exterior finishes tested were as follows: (1) horizontal ship-lap lumber siding; (2) horizontal ship-lap lumber siding over diagonal lumber sheathing; and (3) T1-11 wood structural panels. Details for the geometry and application for the wet exterior finishes can be found in Schiller et al. [2020(a)], while details for the dry exterior finishes can be found in Schiller et al. [2020(b)]. Per *FEMA P-1100*, framing details for all specimens as well as methods adopted to retrofit the specimens can be found in these reports. All cripple walls presented in this report were constructed with the same boundary conditions. Details of the boundary conditions can be found in the first report by Schiller et al. [2020(a)].

Table 2.1 denotes the unique variables considered in the testing program, with specimens labeled A-1 through A-28; the test number was defined by the order of testing. The first and fourth phase included six cripple walls each, and the second and third phase included eight each. This table includes a reference to the specific report that contains details of the specimens in response to the testing. The following section provides a brief recap of the test setup along with a description of the instrumentation and the loading protocol adopted. In the interest of providing a concise presentation, a short name was adopted for each specimen; see Table 2.2. It should be noted that in Table 2.2, test specimens from Phase 1 testing are not included. These tests are omitted from the report because they do not offer direct comparisons to the specimens in Phases 2–4 testing because the boundary conditions of the Phase 1 tests were unique to that phase, whereas the boundary conditions in the other testing phases were alike.

Table 2.1 Small-component complete testing matrix.

Testing phase	Report no.†	Specimen	Test no.	Existing or retrofitted	Era	Vertical load	Cripple wall height (ft)	Anchorage	Exterior finish	Top BC	Bottom BC	Loading	Test date
1	1	A-1	4	E	Pre-1945	H	2	S(64 in.)	S+HSh	**A**	**a**	C	**1/26/2018**
		A-2	3	E	Pre-1945	H	2	S(64 in.)	S+HSh	B	**a**	C	**1/18/2018**
		A-3	6	E	Pre-1945	H	2	S(64 in.)	S+HSh	**C**	**a**	C	**2/2/2018**
		A-4	1	E	Pre-1945	H	2	S(64 in.)	S+HSh	B	**b**	C	**12/18/2017**
		A-5	5	**R**	Pre-1945	H	2	**S(32 in.)**	S+HSh	B	**a**	C	**1/31/2018**
		A-6	2	E	Pre-1945	H	2	**WS**	S+HSh	B	**b**	C	**12/22/2017**
2	2	A-7	7	E	1945–1955	H	2	S(64 in.)	HS	B	c	C	**5/11/2018**
		A-8	8	**R**	1945–1955	H	2	**S(32 in.)**	HS	B	c	C	**5/22/2018**
		A-9	11	E	1945–1955	H	2	S(64 in.)	HS+DSh	B	c	C	**7/19/2018**
		A-10	12	**R**	1945–1955	H	2	**S(32 in.)**	HS+DSh	B	c	C	**7/26/2018**
		A-11	9	E	1956–1970	H	2	S(64 in.)	T	B	c	C	**6/15/2018**
		A-12	10	**R**	1956–1970	H	2	**S(32 in.)**	T	B	c	C	**6/28/2018**
		A-13	13	E	1945–1955	H	**6**	S(64 in.)	HS	B	c	C	**8/26/2018**
		A-14	14	**R**	1945–1955	H	**6**	**S(32 in.)**	HS	B	c	C	**8/30/2018**
3	3	A-15	20	E	Pre-1945	H	2	S(64 in.)	S+DSh	B	c	C	**11/20/2018**
		A-16	21	**R**	Pre-1945	H	2	**S(32 in.)**	S+DSh	B	c	C	**2/5/2019**
		A-17	18	E	Pre-1945	H	2	S(64 in.)	S	B	**d**	C	**11/5/2018**
		A-18	22	**R**	Pre-1945	H	2	**S(32 in.)**	S	B	**d**	C	**11/13/2018**
		A-19	19	**R**	Pre-1945	H	2	**S(32 in.)**	S+HSh	B	c	C	**10/22/2018**
		A-20	15	**E**	Pre-1945	H	2	S(64 in.)	S+HSh	B	**d**	C	**10/31/2018**
		A-21	17	E	Pre-1945	H	2	**WS**	S+HSh	B	c	C	**10/26/2018**
		A-22	16	E	Pre-1945	H	2	S(64 in.)	S	B	c	C	**10/29/2018**
4	2	A-23	23	E	1956–1970	H	**6**	S(64 in.)	T	B	c	C	**9/16/2019**
		A-24	24	**R**	1956–1970	H	**6**	**S(32 in.)**	T	B	c	C	**10/3/2019**
	3	A-25	27	E	Pre-1945	H	**6**	S(64 in.)	S	B	c	C	**10/29/2019**
		A-26	28	**R**	Pre-1945	H	**6**	**S(32 in.)**	S	B	c	C	**11/7/2019**
		A-27	26	E	Pre-1945	H	2	S(64 in.)	S+HSh	B	c	**M**	**10/25/2019**
	2	A-28	25	E	1945–1955	**L**	2	S(64 in.)	HS+DSh	B	c	C	**10/10/2019**
Denotes Pre-1945 Era				Retrofitted		Low vertical Load		Wet set sill or retrofitted	Dry finish materials	Case A,C	Case a,b,d	Monotonic loading	
Denotes 1945–1955 Era													
Denotes 1956–1970 Era													

Notes: E = existing R = retrofitted, H = heavy vertical load (450 plf), L = light vertical load (150 plf), S(XX in.) = anchor bolt spacing, WS = wet set sill plate, S = stucco, HS = horizontal siding, HSh = horizontal sheathing, DSh = diagonal sheathing, T = T1-11 wood structural panels, BC = boundary condition, uppercase letters = top boundary conditions, lowercase letters = bottom boundary condition, C = cyclic, and M = monotonic.

†Reports are as follows: Report 1: Schiller et al. [2020(a)], Report 2: Schiller et al. [2020(b)], and Report 3: Schiller et al. [2020(c)]. Note that boundary conditions are defined in Report 1.

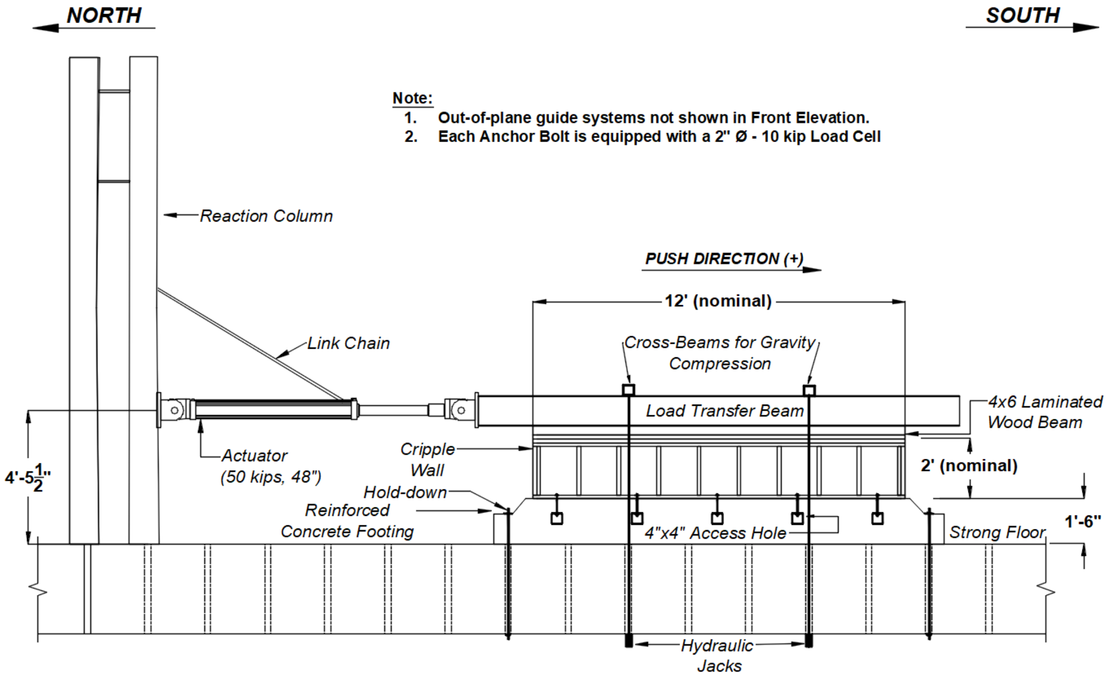
Table 2.2 **Variable parameters for each cripple wall tested and specimen pseudo-names.**

Specimen name	Test no.	Description of test	Specimen pseudo-name†
A-7	7	Horizontal siding, existing 2 ft tall	2 ft HS
A-8	8	Horizontal siding, retrofitted 2 ft tall	2 ft HS Retrofit
A-9	11	Horizontal siding over diagonal sheathing, existing 2 ft tall	2 ft HS+DSh
A-10	12	Horizontal siding over diagonal sheathing, existing 2 ft tall	2 ft HS+DSh Retrofit
A-11	9	T1-11 wood structural panel, existing 2 ft tall	2 ft T1-11
A-12	10	T1-11 wood structural panel, retrofitted 2 ft tall	2 ft T1-11 Retrofit
A-13	13	Horizontal siding, existing 6 ft tall	6 ft HS
A-14	14	Horizontal siding, retrofitted 6 ft tall	6 ft HS Retrofit
A-15	20	Stucco over diagonal sheathing, existing 2 ft tall	2 ft S+ DSh
A-16	21	Stucco over diagonal sheathing, retrofitted 2 ft tall	2 ft S+DSh Retrofit
A-17	18	Stucco, existing 2 ft tall, bottom BC: d	2 ft S (d)
A-18	22	Stucco, retrofitted 2 ft tall, bottom BC: d	2 ft S Retrofit (d)
A-19	19	Stucco over horizontal sheathing, retrofit, 2 ft tall	2 ft S+HSh Retrofit
A-20	15	Stucco over horizontal sheathing, existing 2 ft tall, bottom BC: d	2 ft S+HSh
A-21	17	Stucco over horizontal sheathing, existing wet set sill, 2 ft tall	2 ft S+HSh WS
A-22	16	Stucco, existing 2 ft tall	2 ft S
A-23	23	T1-11 wood structural panel, existing 6 ft tall	6 ft T1-11
A-24	24	T1-11 wood structural panel, retrofitted, 6 ft tall	6 ft T1-11 Retrofit
A-25	26	Stucco, existing 6 ft tall	6’ S
A-26	27	Stucco, retrofitted 6 ft tall	6 ft S Retrofit
A-27	28	Stucco over horizontal sheathing, existing monotonic, 2 ft tall	2 ft S+HSh M
A-28	25	Horizontal siding over diagonal sheathing, existing light vertical load 2 ft tall	2 ft HS+DSh (Light)

† For acronyms, see Table 2.1

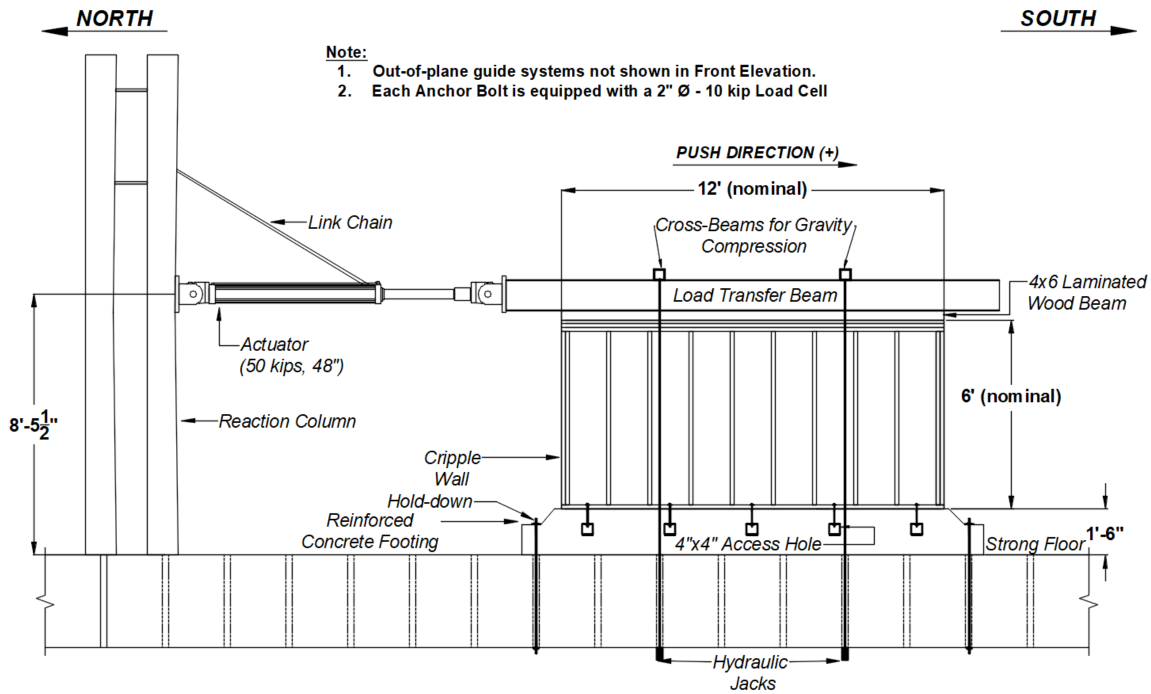
2.2 TEST SETUP

Figure 2.1 shows a plan view and elevation views of the test setup for both the 2-ft-tall and 6-ft-tall specimens. A complementary photograph of the 2-ft-tall test setup is shown in Figure 2.2. It should be noted that for Specimens A-1 through A-6, the push loading direction was north, and the pull direction was south as the tests for these specimens were conducted in another laboratory. The lateral load was applied with a 48-in. (total) stroke, servo-controlled, hydraulic horizontal actuator capable of imposing 50 kips. The actuator was mounted to a strong wall using an actuator mounting plate, with its weight carried via a link chain back to the reaction wall so as to not impose a vertical load on the cripple wall. The lateral force was transferred from the actuator to the cripple wall with a stiff steel beam (W12 × 26 section). To allow for uninhibited movement of the finishes and plywood panels, particularly when present in retrofit walls, during testing, a 4 × 6 pressure-treated wood beam was used as a spacer between the steel beam and the uppermost top plate of the cripple wall. This also facilitated ease of assembly of the specimens.



Elevation
2' Tall Cripple Wall Test Setup

(a)



Elevation
6' Tall Cripple Wall Test Setup

(b)

Figure 2.1 Test setup; (a) elevation for the 2-ft-tall cripple wall (interior face); and (b) elevation for the 6-ft-tall cripple wall (interior face).

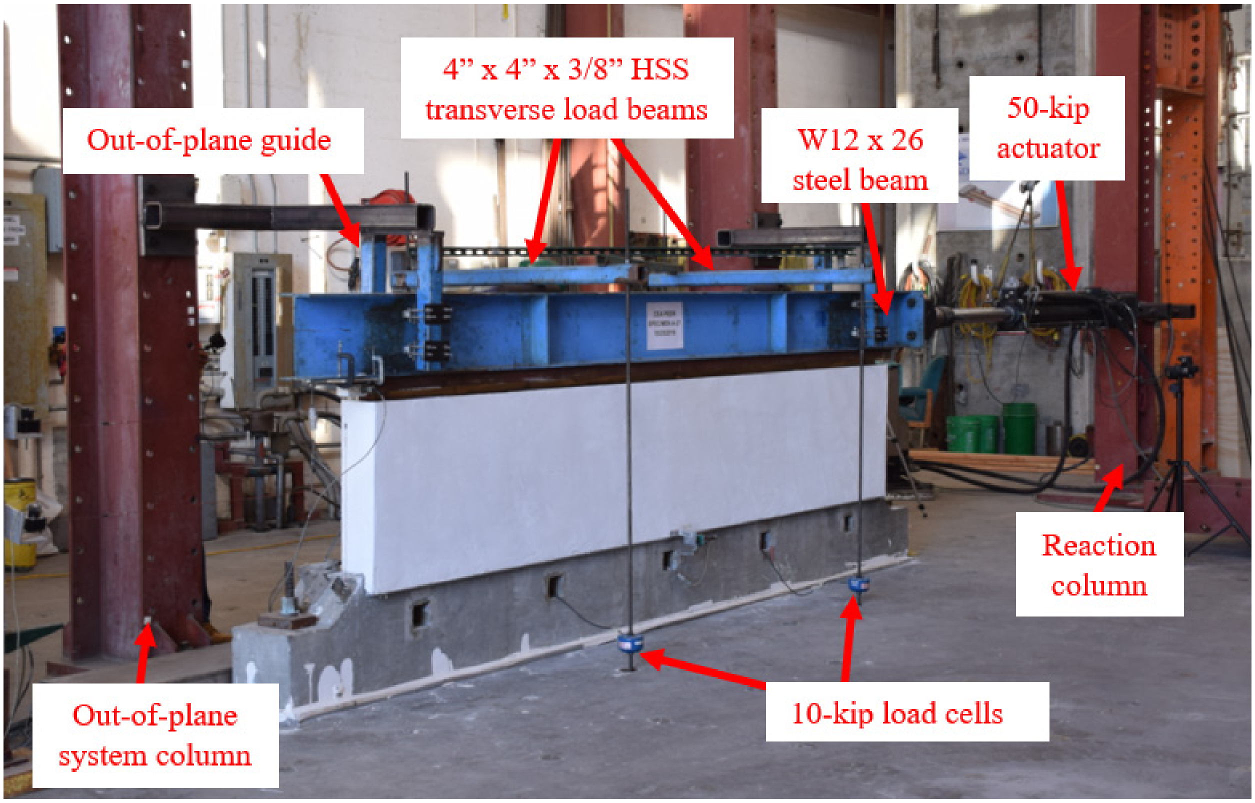


Figure 2.2 Specimen A-27 isometric view of the test setup for 2-ft-tall cripple walls.

When possible, the concrete footing was reused for each test; it was fastened to the strong floor with a rod at each end, each tensioned to 50 kips. Once individual specimens were constructed and placed in the testing apparatus, the laminated wood beam and steel beam were attached. Subsequently, two HSS sections were placed transversely at third points along the specimen as they were utilized to apply vertical load to the steel beam. Each transverse HSS beam had a 1/2-in.- diameter all-thread rod attached at each end. The threaded rods were attached to the transverse beams and hydraulic jacks at the base of the strong floor. The hydraulic jacks were used to apply the desired vertical load to each specimen. The choice of location for applying the loads was meant to approximate a uniformly distributed gravity load on the full length of the cripple wall specimen. The stiff W12 × 26 lateral transfer beam was deemed sufficient to nominally result in a uniform load application. It is noted that 400 lbs of the target 5400 lbs (450 plf case) were available via the weight of the lateral steel and wood laminated transfer beams, thus the transverse HSS assembly required application of an additional 1250 lbs per point load location.

Before any loads were applied to the cripple wall, pairs of rollers were fastened to the sides of the out-of-plane guide. The rollers were greased, and a 1/16-in. gap was left between the steel plate and the steel transfer beam to avoid any artificial loads via friction force at the contact interface of the plates and beam. The purpose of implementing an out-of-plane guide system was to ensure that the imposed displacement during testing is only in-plane. Once the vertical load was applied to the test setup, the anchor bolts were tensioned. For the first phase of testing, each anchor bolt was tensioned between 0.2–4.0 kips; in subsequent testing phases, each anchor bolt was tensioned to 200 lbf. The change in anchor bolt tensioning was made to mimic the amount of tension commonly seen in anchor bolts of existing California homes that would be most akin to a "hand-tightened" condition. Once the anchor bolts were tensioned, a bias of all instrumentation including the actuator load and displacement was made, and all values were recorded before and after the bias. The bias ensures that all instrumentation begins with a zero value, with the exception in these tests of the load cells, which are tightened prior to commencing with application of lateral loading, therefore their loads are retained, i.e., unbiased. At this point, the test would begin.

Extensive measurements of displacements, rotations, and loads were performed on each cripple wall specimen. Each specimen had slight variations in instrumentation depending on its boundary conditions and retrofitting condition which can be referred to in the previous reports. The overall response of the cripple wall was characterized using displacements measured by displacement transducers. One displacement transducer attached to the middle of each specimen's upper top plate measured the overall displacement imposed on the cripple wall. An additional displacement transducer was attached to the middle of the sill plate to measure the displacement of the sill plate relative to the foundation. By taking the difference between LP01 and LP03, the relative displacement of the cripple wall could be determined (neglecting sill-to-foundation displacement). Additional details on instrumentation and their locations can be found in Schiller et al. [2020(b) and (c)]. The tension in each anchor bolt was measured with a 10-kip load cell. Additional 10-kip load cells were used to measure the applied vertical load. Pairs of diagonal displacement transducers measured the shear distortion across the entire specimen as well as the middle third of the specimen. The uplift was measured with displacement transducers at both ends of the cripple walls. Inclinometers were used to measure the longitudinal and transverse rotation of the specimens. Additional displacement transducers were used to measure siding, sheathing, stucco, and plywood displacement.

2.3 LOADING PROTOCOL

The loading protocol for each test varied slightly depending on the rate of post-peak strength degradation of the individual specimen. All cripple walls underwent the same loading protocol up until the specimen realized a loss greater than 60% of its measured peak lateral strength. At this point in the protocol, the following and each subsequent drift ratio level was increased by 2% rather than 1%. If the 60% loss in strength did not occur, each drift ratio level would remain at an increase of 1% per cycle grouping. The loading protocol would progress until an 80% loss in strength was realized. At this point, a monotonic push would be conducted, typically to a global drift of 20%. The amplitude of the monotonic push might have varied slightly depending on instrumentation constraints. Figure 2.3 shows the loading protocol for Specimen A-7 (a 2-ft-tall cripple wall), and Table 2.3 provides a specific summary of the amplitudes and cycle counts associated with the loading protocol for this specific specimen. Similarly, Figure 2.4 shows the loading protocol for Specimen A-13 (a 6-ft-tall cripple wall), while Table 2.4 provides numerical details of this loading protocol.

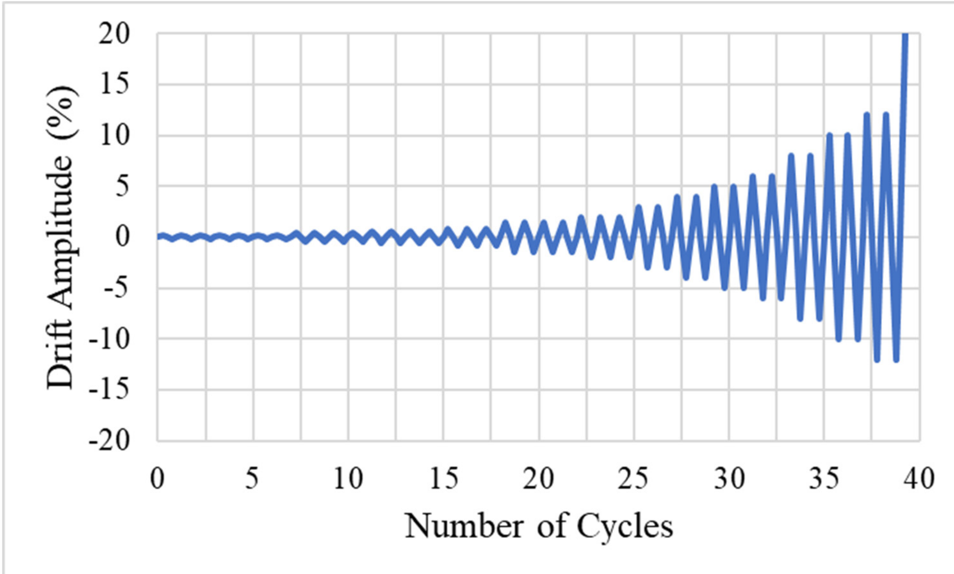


Figure 2.3 **Loading protocol for Specimen A-7 (2-ft-tall specimen).**

Table 2.3 **Summary of loading protocol for Specimen A-7 (2-ft-tall specimen).**

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loading rate (in./sec)	Time per cycle (sec)	Total time per cycle group (sec)
1	0.2	0.048	7	0.0064	30	210
2	0.4	0.096	4	0.0128	30	120
3	0.6	0.144	4	0.0192	30	120
4	0.8	0.192	3	0.0256	30	90
5	1.4	0.336	3	0.0448	30	90
6	2	0.48	3	0.064	30	90
7	3	0.72	2	0.096	30	60
8	4	0.96	2	0.128	30	60
9	5	1.2	2	0.16	30	60
10	6	1.44	2	0.192	30	60
11	8	1.92	2	0.256	30	60
12	10	2.4	2	0.16	60	120
13	12	2.88	2	0.192	60	120
14	Mono	5.0	--	0.333	60	60

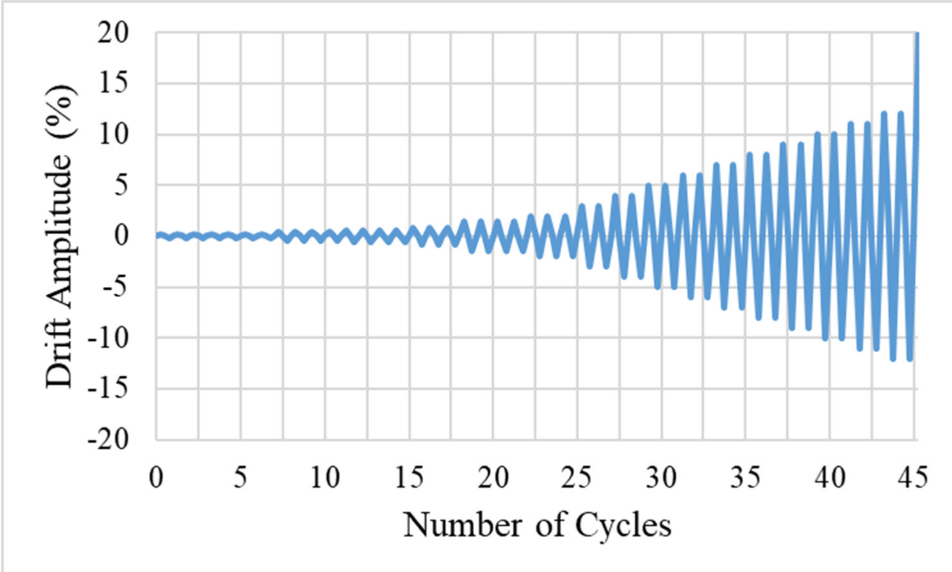


Figure 2.4 Loading protocol for Specimen A-13 (6-ft-tall specimen).

Table 2.4 Summary of loading protocol for Specimen A-13 (6-ft-tall specimen).

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loading rate (in./sec)	Time per cycle (sec)	Total time per cycle group (sec)
1	0.2	0.144	7	0.0192	30	210
2	0.4	0.288	4	0.0384	30	120
3	0.6	0.432	4	0.0576	30	120
4	0.8	0.576	3	0.0768	30	90
5	1.4	1.008	3	0.1344	30	90
6	2	1.44	3	0.096	60	180
7	3	2.16	2	0.144	60	120
8	4	2.88	2	0.192	60	120
9	5	3.6	2	0.24	60	120
10	6	4.32	2	0.288	60	120
11	7	5.04	2	0.336	60	120
12	8	5.76	2	0.192	120	240
13	9	6.48	2	0.216	120	240
14	10	7.20	2	0.24	120	240
15	11	7.92	2	0.264	120	240
16	12	8.64	2	0.288	120	240
17	Mono	15.0	--	0.333	180	180

3 Test Results

3.1 GENERAL

This chapter presents results of the reversed cyclic response of select cripple walls in the testing program. The selection is intended to compare the various exterior finishes tested with emphasis on cripple wall height and retrofitted condition. While there are many key parameters in this testing program, including exterior finish, height, boundary condition, retrofitted condition, vertical load, loading protocol, and anchorage condition, the comparisons made in this chapter are only between specimens that varied in their exterior finish and have the same respective height and retrofitted condition. All specimens presented were tested reversed cyclically with a vertical load of 450 plf, top boundary condition B, bottom boundary condition c, and a typical anchorage (anchor bolts).

The only exception was for Specimen A-20, which was the existing 2-ft-tall specimen with stucco over horizontal sheathing with bottom boundary condition "d." This boundary condition included an extension of the stucco down the face of the footing, which was not the case with bottom boundary condition c. However, the bond between the stucco and the foundation was severely weakened prior to testing, therefore, the response of Specimen A-20 was not significantly influenced by the extension of the stucco and can be compared with other cripple walls with like height and retrofitted condition. The vertical load applied mimicked the gravity load of a two-story house constructed with heavy building materials. Top boundary condition B and bottom boundary condition "c" were the baseline boundary conditions for the testing program. Details of the boundary conditions can be found in the first report by Schiller et al. [2020(a)]. There were six exterior finishes tested, three wet or stucco finishes, and three dry or non-stucco finishes. The wet exterior finishes were as follows: (1) stucco over framing; (2) stucco over horizontal lumber sheathing; and (3) stucco over diagonal lumber sheathing. The dry exterior finishes were as follows: (1) horizontal shiplap lumber siding; (2) horizontal shiplap lumber siding over diagonal lumber sheathing; and (3) T1-11 wood structural panels. The two cripple wall heights were tested: 2-ft-tall walls and 6-ft-tall walls, and all cripple walls were around 12 ft in length. The retrofit design followed the guidelines of the *FEMA P-1100* prescriptive design provisions. Each specimen of a particular exterior finish and height had a retrofitted counterpart.

3.2 LATERAL FORCE–LATERAL DISPLACEMENT RESPONSE

This section presents the lateral force-displacement responses for the varying exterior finishes. The presentation includes overlays of the envelopes of the lateral force-displacement hysteresis with varying exterior finishes; see Figure 3.1 through Figure 3.8. Each figure presents specimens with the same height and retrofitted condition. It is noted that both global total and global relative displacement are presented, where the relative displacement accounts for the displacement of the cripple wall only and ignores displacement between the foundation and the sill plate. In addition, secondary axes were incorporated in each plot to present the lateral load per lineal foot of wall length and the drift ratio (i.e., displacement/cripple wall height). Overlays of the lateral force-displacement relative response are provided for direct comparisons between wet and dry specimens, as shown in Figure 3.9 through Figure 3.14. As with the envelopes, the specimens only differed in their exterior finish. It should be noted that maximum lateral load in the positive and negative directions are identified in each hysteresis. Figure 3.15 through Figure 3.26 show the lateral strength per linear foot, global drift ratio at strength, and relative drift ratio at strength for select specimens with various exterior finishes grouped with the same height and retrofit condition.

3.2.1 Lateral Strength

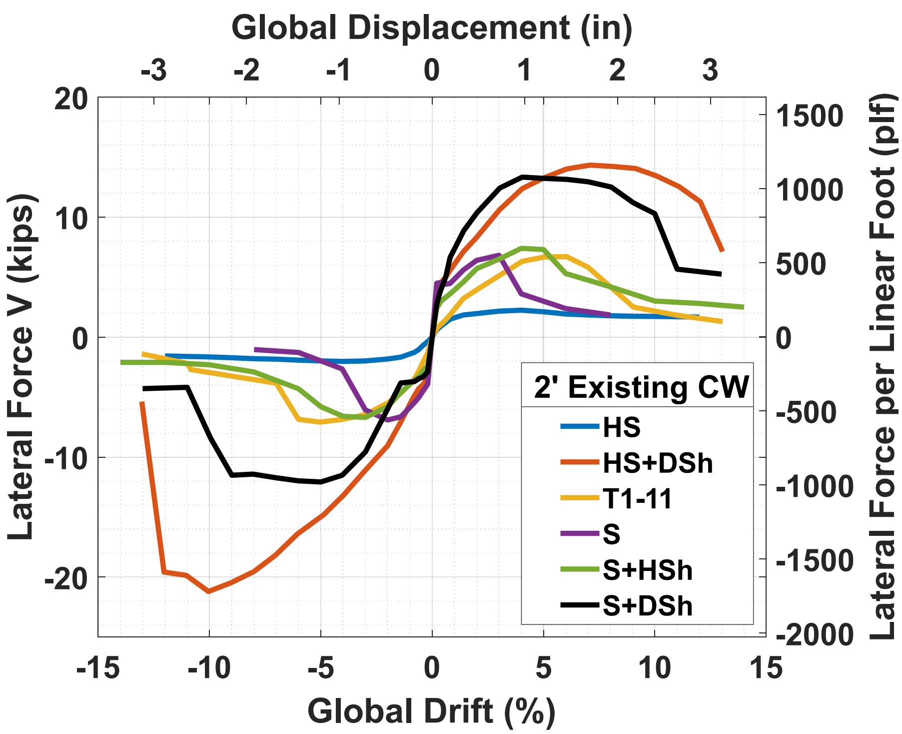
3.2.1.1 Existing Specimens

Two-Foot-Tall Specimens

The global and relative lateral force-displacement hysteresis for the existing 2-ft-tall specimens are shown in Figure 3.1 and Figure 3.2, respectively. The lateral strength for each specimen is provided in Figure 3.3. For the existing 2-ft-tall cripple walls for, amongst all specimen finish types for those unretrofitted, diagonal sheathing was the strongest exterior finish material. The average lateral strength per linear foot in push and pull loading was 1435 plf for the horizontal siding over diagonal sheathing specimen and 1027 plf for the stucco over diagonal sheathing specimen. These were the only two existing specimens that experienced anchor bolt fractures or large cross-grain cracks in the sill plate; therefore, the full strength of the finish was likely not achieved for either specimen.

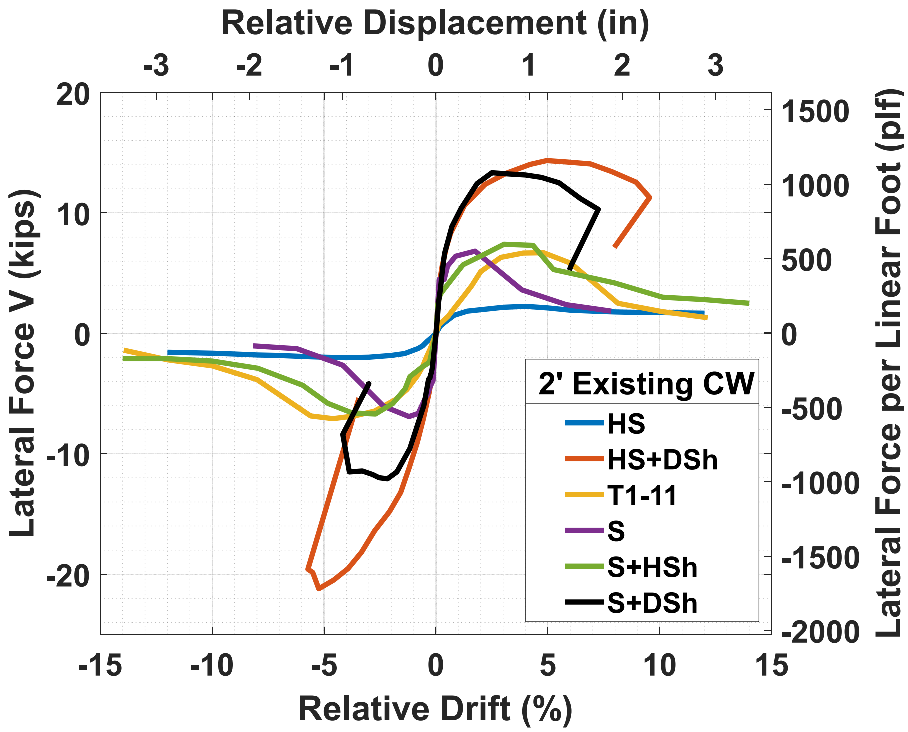
The orientation of the diagonal sheathing boards produced larger strengths during pull loading where the gaps between the sheathing boards would close. As the gaps between the boards closed, the sheathing began to bear on each other. This produced a phenomenon where the boards would act in unison, producing the effect of a wood structural panel. The effect increased not only the strength but also the drift capacity of the specimen in the pull loading direction. For the horizontal siding over diagonal sheathing specimen, the sill plate and anchor bolts stayed intact long enough in the displacement cycles for this phenomenon to occur, as shown by a nearly 50% increase in the pull loading direction (1713 plf) over the push loading direction (1156 plf). It was not, however, experienced by the stucco over diagonal sheathing specimen, which lost strength once a cross-grain crack in the sill plate had propagated across the length of the sill plate through the location of the anchor bolts. With the anchor bolts no longer able to provide resistance to the imposed displacement, the load dropped, with much of the strength due to the frictional resistance between the sill plate and foundation. The stucco over diagonal sheathing specimen had a lateral strength of 1079 plf in the push loading direction and 975 plf in the pull loading direction. Even with the sill plate failure, the lateral strength was over 80% higher than the next strongest cripple wall, which was finished with stucco over horizontal sheathing.

The stucco over framing, stucco over horizontal sheathing, and T1-11 wood structural panels exterior finishes produced strengths that were within 5% of each other. The response of these three specimens were nearly symmetric, as shown in Figure 3.1 and Figure 3.2. The stucco over horizontal sheathing and T1-11 wood structural panel finished cripple walls had nearly identical strengths, with average values in push and pull directions of 569 plf and 568 plf, respectively. The average lateral strength of the stucco over framing specimen was 5% less than both specimens (551 plf). By a wide margin, the weakest specimen amongst all dry and wet unretrofitted specimens tested was the specimen finished with horizontal siding. The capacity of the horizontal siding specimen (172 plf) was 31% of the stucco over framing specimen, which was the next weakest specimen. The siding boards were oriented so that the only resistance to displacement was provided through moment couples developed between the nails fastening the boards to the framing and the friction at the 3/8-in. gap between the boards.



Legend: HS = horizontal siding; S = stucco only; HS+DSh = horizontal siding over diagonal sheathing; T1-11 = T1-11 wood structural panels; S+HSh = stucco over horizontal sheathing; S+DSh = stucco over diagonal sheathing.

Figure 3.1 Envelope of lateral force versus *global* lateral drift and displacement hysteresis of the existing 2-ft-tall specimens with various exterior finishes.



Legend: HS = horizontal siding; S = stucco only; HS+DSh = horizontal siding over diagonal sheathing; T1-11 = T1-11 wood structural panels; S+HSh = stucco over horizontal sheathing; S+DSh = stucco over diagonal sheathing.

Figure 3.2 Envelope of lateral force versus *relative* lateral drift and displacement hysteresis of the existing 2-ft-tall specimens with various exterior finishes.

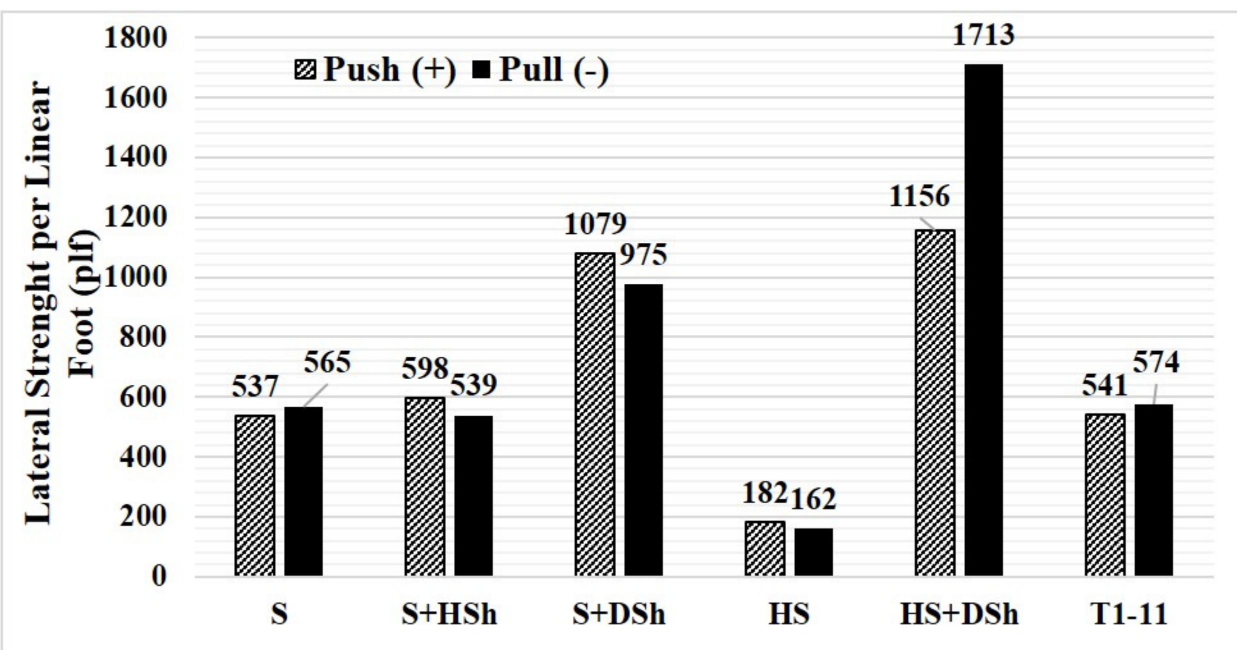


Figure 3.3 Comparison of lateral strength per linear foot of the existing 2-ft-tall cripple walls with various exterior finishes.

Existing Six-Foot-Tall Specimens

The global and relative force-displacement envelopes for existing 6-ft-tall specimens are shown in Figure 3.4 and Figure 3.5, respectively. The lateral strength for each specimen is summarized in Figure 3.6. The three exterior finishes tested were stucco over framing, horizontal siding, and T1-11 wood structural panels. The strongest specimen was the stucco finished cripple wall with an average lateral strength of 645 plf. This lateral strength was more than 70% larger compared to the T1-11 finished cripple wall, which had an average lateral strength of 379 plf and nearly 600% larger than the horizontal siding cripple wall, which had an average lateral strength of 93 plf. With the 2-ft-tall cripple walls, the strength of the T1-11 and stucco finished cripple walls were within 5% of each other. This is a significant difference compared to the response of the 6-ft-tall cripple walls.

The relative difference could be due to the nailing pattern of the T1-11 cripple wall. The T1-11 panels were only fastened with nails on the top, bottom, and a single edge. At the panel overlaps, which occurred on one edge within the interior of the specimen (i.e., not the free end of the specimen), the overlying panel contained a row of fasteners that sandwiched the underlying panel, thereby keeping it in place. Due to the increased height of the cripple wall, the response was more flexure dominated than shear dominated compared to the 2-ft-tall cripple walls. It is assumed that the increased flexural component as well as the increased length of the un-nailed underlying panel exposed the weakness of the un-nailed panel edge more so compared to the shorter walls. Another difference could be due to the increased rigidity of the fastener connections that the stucco furring nails provided, which was enhanced for the taller specimens. The furring nails were cemented around 1/4 in. into the stucco and embedded around 2 in. into the framing. For the T1-11 finished cripple wall, the nails were fastened through the T1-11 panel into the framing, which is a less rigid connection as the fasteners were able to rotate more freely. The stucco cripple wall fasteners were fully mobilized at lower amplitude displacement cycles compared to the T1-11 cripple wall fasteners, resulting in the stucco cripple wall achieving strength at earlier displacement cycles compared to the T1-11 cripple wall; see Figure 3.3 and Figure 3.4. As with the shorter specimens, the horizontal siding cripple wall had the lowest lateral strength amongst those finish types tested.

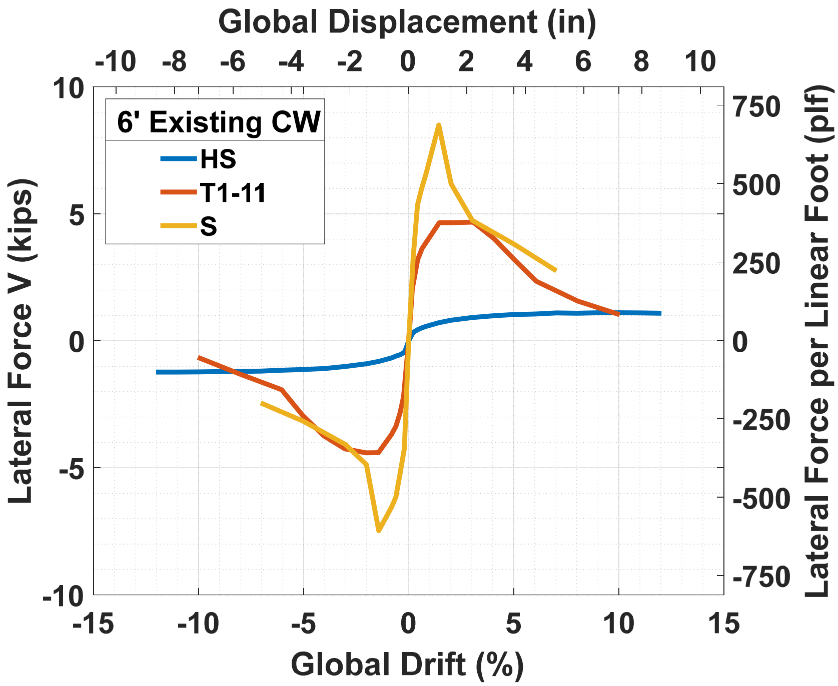


Figure 3.4 Envelope of lateral force versus *global* lateral drift and displacement hysteresis of the existing 6-ft-tall specimens with various exterior finishes.

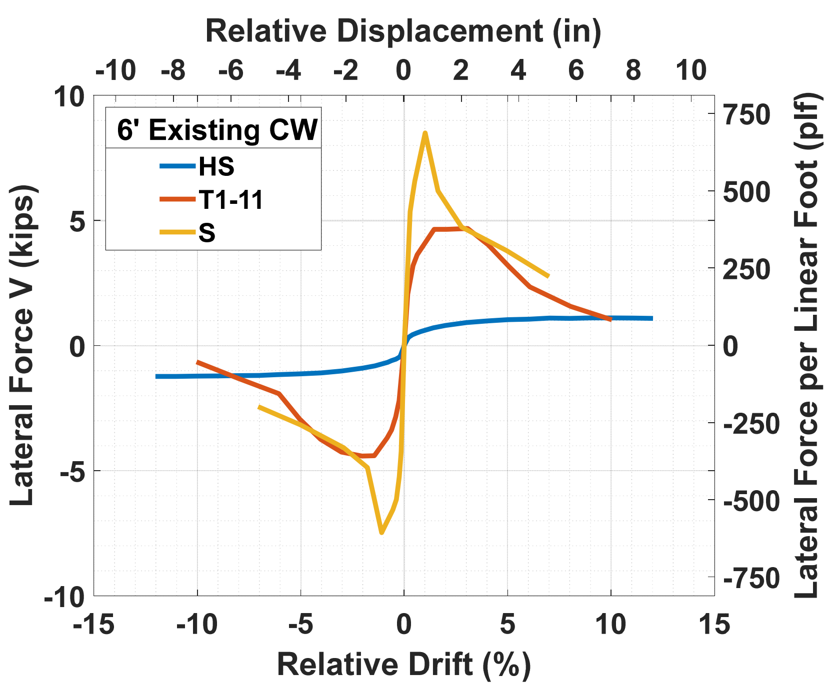


Figure 3.5 Envelope of lateral force versus *relative* lateral drift and displacement hysteresis of existing 6-ft-tall specimens with various exterior finishes.

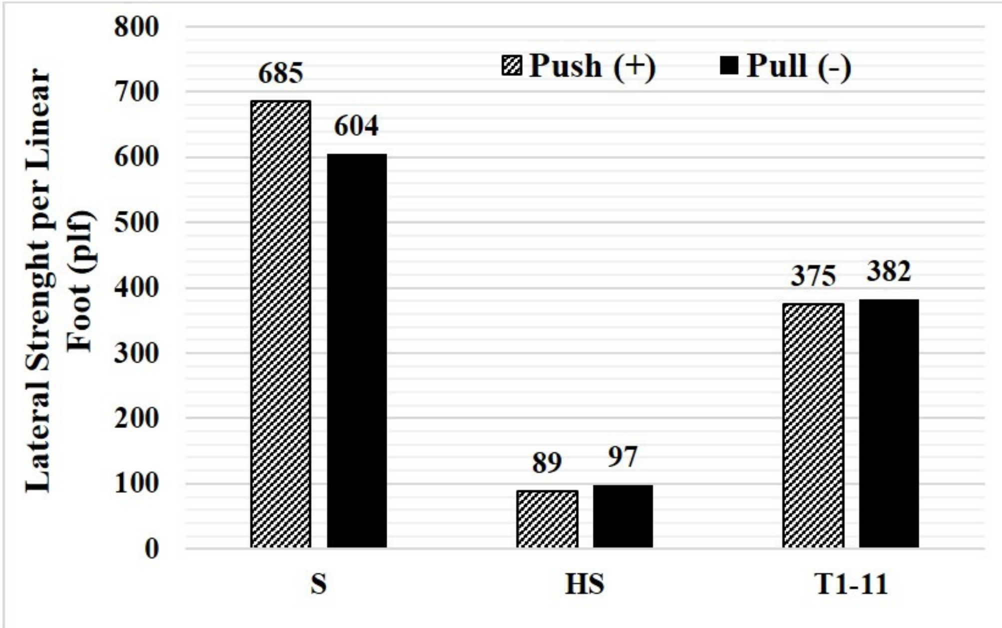


Figure 3.6 **Comparison of lateral strength per linear foot of the existing 6-ft-tall cripple walls with various exterior finishes.**

3.2.1.2 Retrofitted Specimens

Retrofitted Two-Foot-Tall Specimens

The global and relative force-displacement envelopes for retrofitted 2-ft-tall specimens are shown in Figure 3.7 and Figure 3.8, respectively. The lateral strength for each specimen is provided in Figure 3.9. As with the existing specimens, cripple walls containing diagonal sheathing were the strongest tested. The average lateral strength for the horizontal siding over diagonal sheathing finished specimen was 2550 plf, and the average lateral strength for the stucco over diagonal sheathing finished specimen was 2037 plf. The specimen with horizontal siding over diagonal sheathing loss strength due to fracturing of all anchor bolts. For the stucco over diagonal sheathing specimen, three of the seven anchor bolts fractured, but ultimately the loss of strength was the result of a large cross-grain crack in the sill plate that propagated across the entire span of the sill plate through the location of the anchor bolts. This was the same phenomenon that occurred in its existing counterpart. It would have been expected that the stucco over diagonal sheathing specimen would have had similar or more strength than the horizontal siding over diagonal sheathing specimen because stucco is a stronger material than horizontal siding. It should be noted that stucco achieved strength at lower displacement amplitudes compared to all other finish materials tested; therefore, the capacity that the stucco provided had peaked prior to strength being obtained. In comparison with horizontal siding, the stucco specimen was stronger compared to the horizontal siding specimen all the way until the end of the test, where the residual strength was nearly identical, see Figure 3.2. Due to the splitting of the sill plate and fracturing of the anchor bolts, the full strength of the finish materials was never realized for either specimen. This is apparent by the more symmetric response of the specimens, demonstrating that the sheathing boards did not provide the full amount of strength that they would have had the gaps between the boards closed, with the panels then coming in contact with each other as what occurred with other specimens.

The stucco over horizontal sheathing, stucco over framing, and horizontal siding finished specimens had lateral strengths within 10% of each other. The weakest of the three finishes was the stucco over framing finished specimen, which had an average lateral strength of 1815 plf in both directions of loading. The strength was nearly identical to the horizontal siding finished specimen, which had an average lateral strength of 1831 plf. Both these walls were around 10% lower in strength capacity of the stucco over horizontal sheathing specimen. The average lateral strength of this specimen was 2037 plf. As stated previously, even though stucco is a stronger material than horizontal siding, the strength is realized at earlier displacement amplitudes compared to the horizontal siding. In addition, the stucco reached strength at earlier displacement amplitudes compared the plywood panels. This explains why the strength of the stucco over framing finished specimen was similar to that of the horizontal siding finished specimen. The T1-11 finished cripple wall had the lowest lateral strength of all the retrofitted specimens, with an average lateral strength of 1103 plf. The strength of the T1-11 finished cripple wall was significantly less than the other retrofitted cripple walls because the edge nail spacing for the T1-11 wood structural panels was at 4 in. on center while the edge nail spacing of the plywood panels was at 3 in. on center. In addition, the T1-11 wood structural paneling was the only material attached to the framing, whereas all the other cripple walls had their exterior finish material(s) and plywood attached to the framing on the interior.

Figure 3.10 shows the percent increase in strength of the retrofitted 2-ft-tall cripple walls. By far the largest increase in strength was observed in the horizontal siding finished specimen, with an average increase of nearly 970%. The next highest increase was for the stucco over horizontal sheathing finished specimen, where the retrofit provided nearly a 260% increase in lateral strength. The retrofit provided a similar amount of increase in strength to the stucco finished specimen, with an increase of 230%. The T1-11 finished cripple wall nearly doubled in strength due to the added retrofit, which was expected due to the edge nail spacing decreasing from 8 in. on center to 4 in. on center.

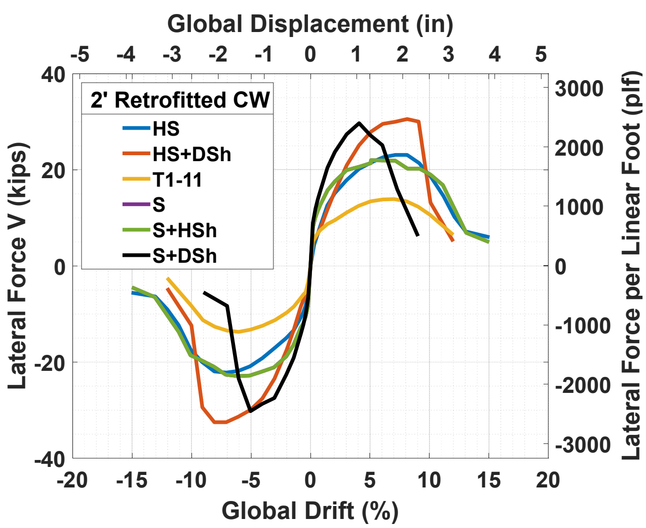


Figure 3.7 **Envelope of lateral force versus *global* lateral drift and displacement hysteresis of the retrofitted 2-ft-wall specimens with various exterior finishes.**

Legend: HS = horizontal siding; S = stucco only; HS+DSh = horizontal siding over diagonal sheathing; T1-11 = T1-11 wood structural panels; S+HSh = stucco over horizontal sheathing; S+DSh = stucco over diagonal sheathing.

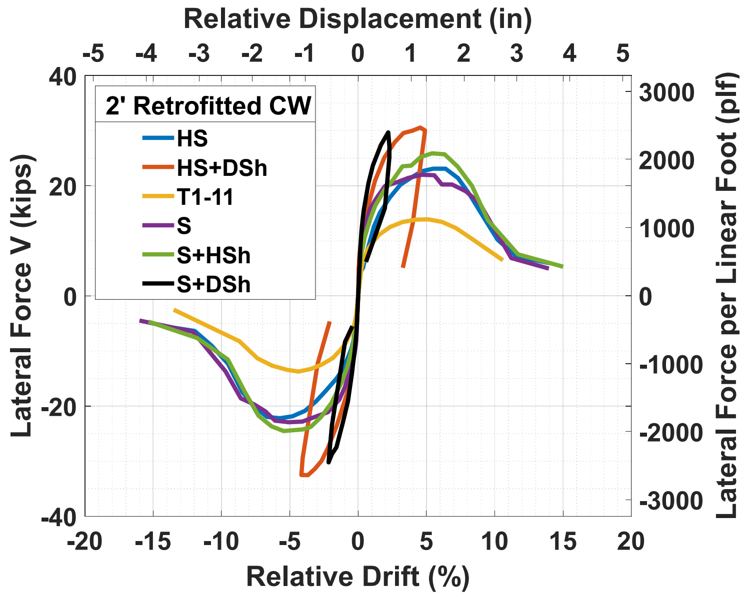


Figure 3.8 Envelope of lateral force versus *relative* lateral drift and displacement hysteresis of the retrofitted 2-ft-wall specimens with various exterior finishes.

<u>**Legend:**</u> HS = horizontal siding; S = stucco only; HS+DSh = horizontal siding over diagonal sheathing; T1-11 = T1-11 wood structural panels; S+HSh = stucco over horizontal sheathing; S+DSh = stucco over diagonal sheathing.

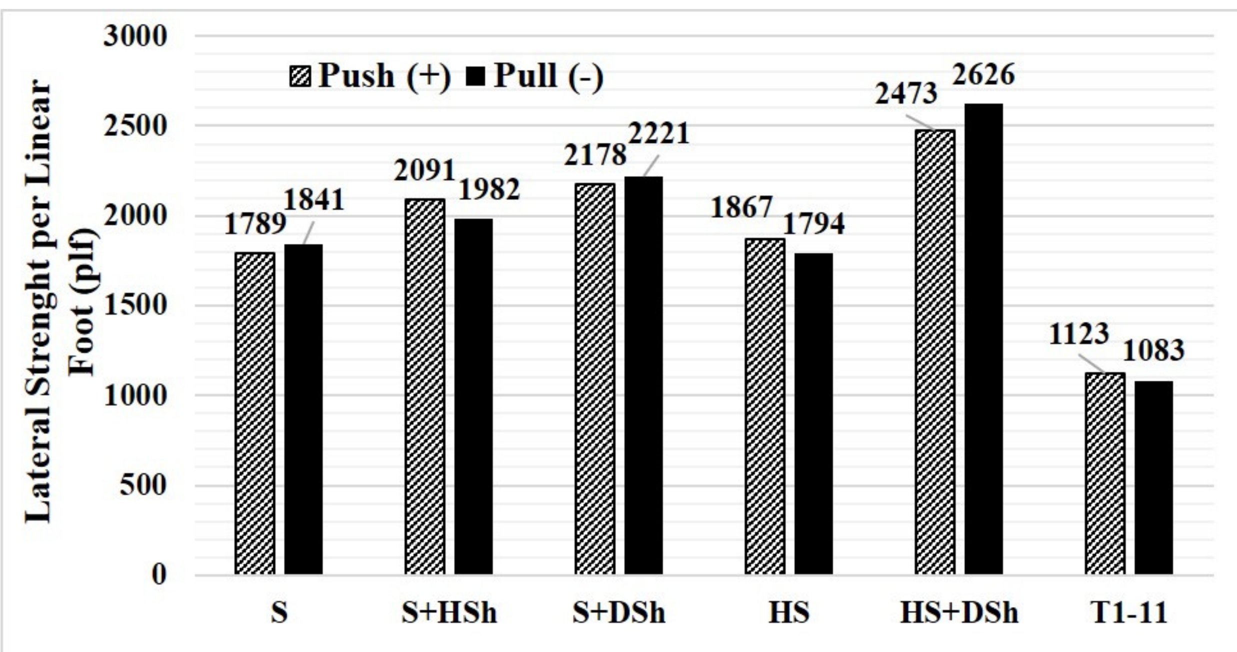


Figure 3.9 Comparison of lateral strength per linear foot of the retrofitted 2-ft-wall cripple walls with various exterior finishes.

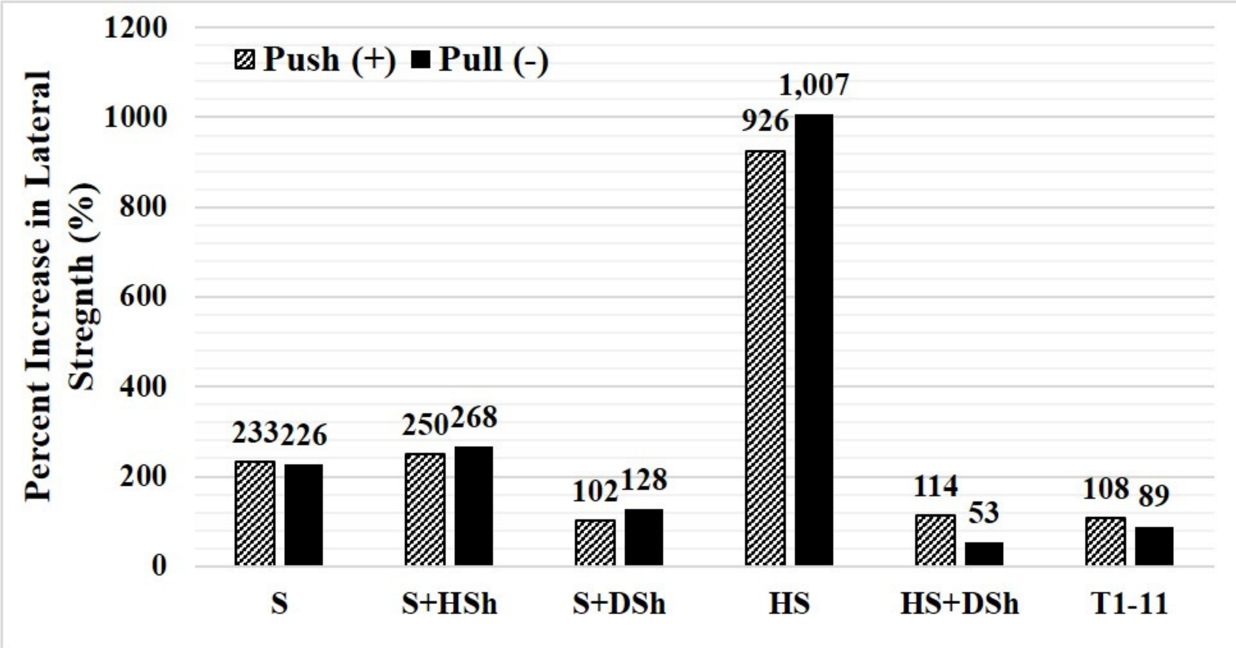


Figure 3.10 **Contribution of retrofit to lateral strength for all retrofitted 2-ft-wall specimens with various exterior finishes.**

Retrofitted Six-Foot-Tall Specimens

The global and relative force-displacement hysteresis for retrofitted 6-ft-tall specimens are shown in Figure 3.11 and Figure 3.12, respectively. The lateral strength for each specimen is provided in Figure 3.13. Of the three specimens tested, the stucco over framing finished specimen had the highest lateral strength of 1814 plf on average considering both directions of loading. This was only around 2% higher than the horizontal siding finish specimen, which had an average lateral strength of 1770 plf. The T1-11 finished cripple wall was considerably lower, with an average lateral strength of 850 plf. This amounted to only 48% the strength capacity of the horizontal siding finished specimen. The large difference in strength between the T1-11 finished specimen and the other specimens was again due to the reduction in edge nail spacing. In addition, it was the only specimen with the finishing material nailed to the framing. With the addition of the retrofit, the horizontal siding finished specimen had the largest relative increase in lateral strength, with an increase of over 1800% compared to its existing counterpart. This is a tenfold increase over the relative contribution of the stucco finished cripple wall. The T1-11 finished cripple wall exhibited the lowest percent increase in lateral strength, which saw only a 125% increase in lateral strength due to the added retrofit. It might have been expected that the lateral strength would have been doubled for this specimen because of the edge nail spacing being reduced by 50%, which was case with the 2-ft-tall specimens. As stated previously, the un-nailed edge on the existing T1-11 finished specimens led to a reduction in capacity relative to the 2-ft-tall specimens due to not only the increased displacement imposed but also the added flexural component. The relative increases in strength of the retrofitted specimens compared with the existing specimens for all 6-ft-tall specimens is provided in Figure 3.14.

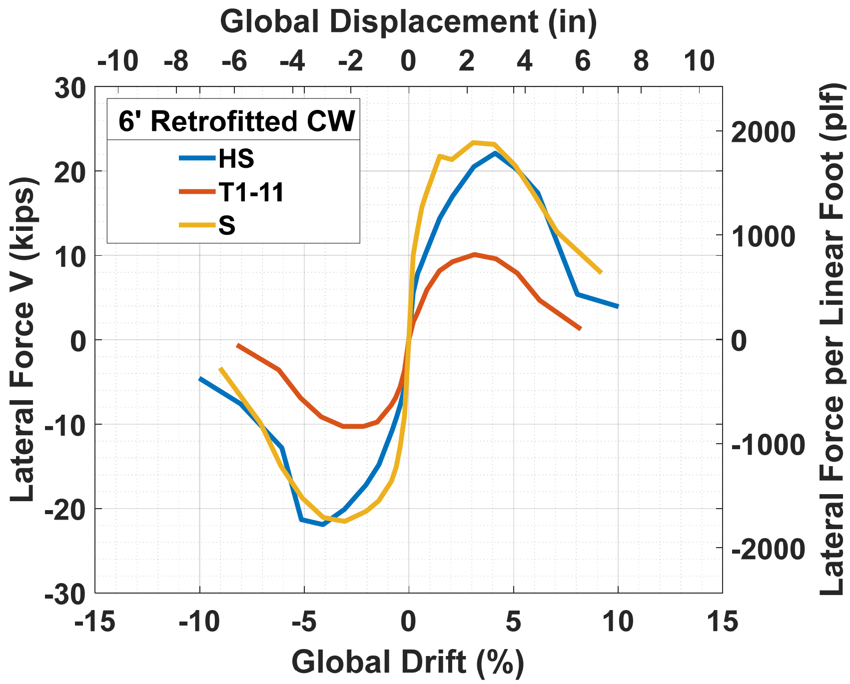


Figure 3.11 Envelope of lateral force versus *global* lateral drift and displacement hysteresis of the retrofitted 6-ft-tall specimens with various exterior finishes.

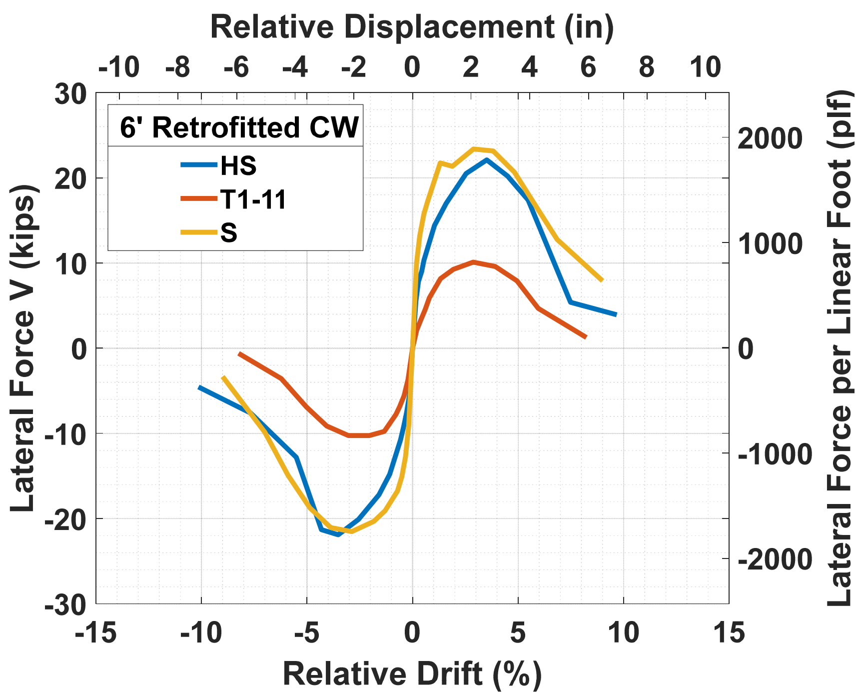


Figure 3.12 Envelope of lateral force versus *relative* lateral drift and displacement hysteresis of the retrofitted 6-ft-tall specimens with various exterior finishes.

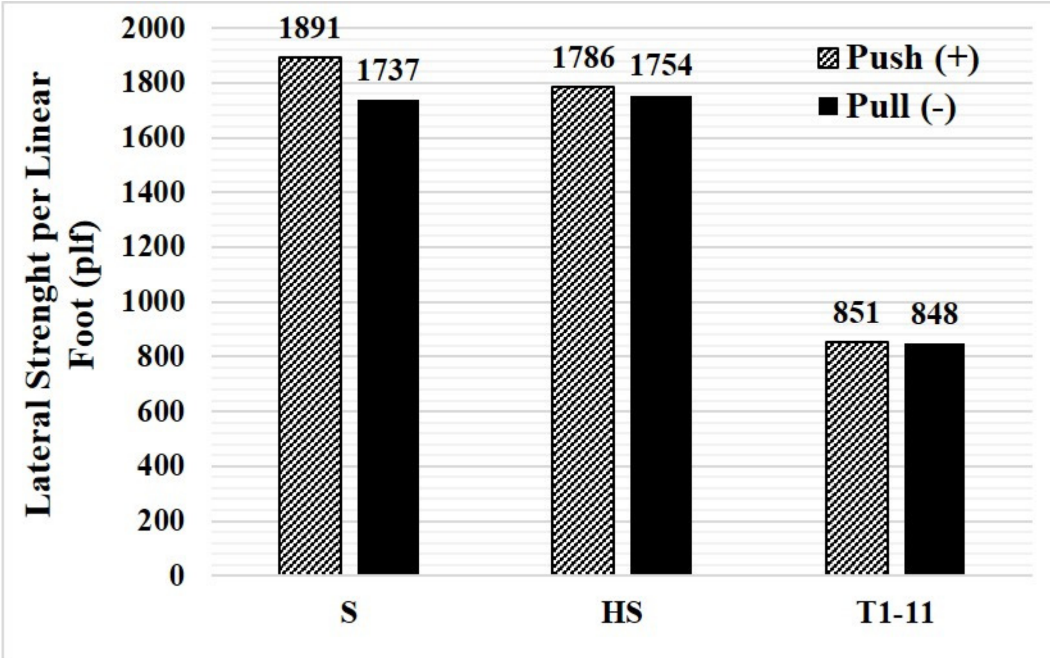


Figure 3.13 Comparison of lateral strength per linear foot of the retrofitted 6-ft-tall cripple walls with various exterior finishes.

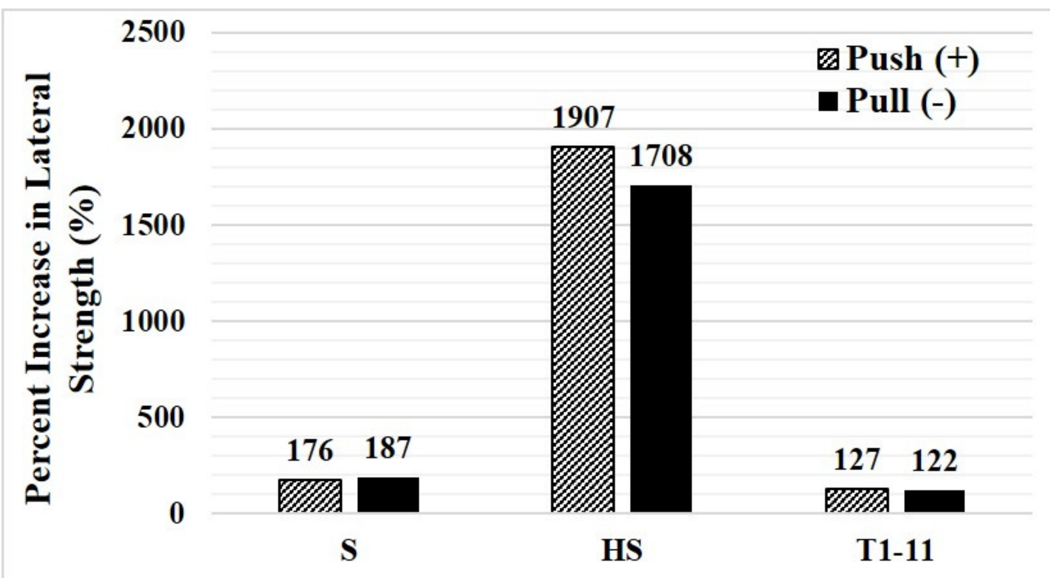


Figure 3.14 Contribution of retrofit to lateral strength for all retrofitted 6-ft-tall specimens with various exterior finishes.

3.2.2 Definition of Key Parameters Across Varying Lateral Load Amplitudes

Important information regarding specimen response can be obtained by studying the pre- and post-peak lateral strength behavior. To this end, Figure 3.15 provides a generic envelope of a cyclic response to illustrate the selected pre- and post-strength values, as adopted in subsequent figures. In what follows, the conceptual strategy articulated in Figure 3.15 is used to determine the drift capacity (also referred to as drift at lateral strength), as well as drift at 80% pre-peak strength and 40% post-peak strength. These values are grouped by wall height and retrofitted condition. Note that drift ratio may be used in some context in the following discussion (adopted interchangeably with drift); the later simply allows a short name reference. Both have the same definition, that is, displacement of interest divided by wall height, and presented in %.

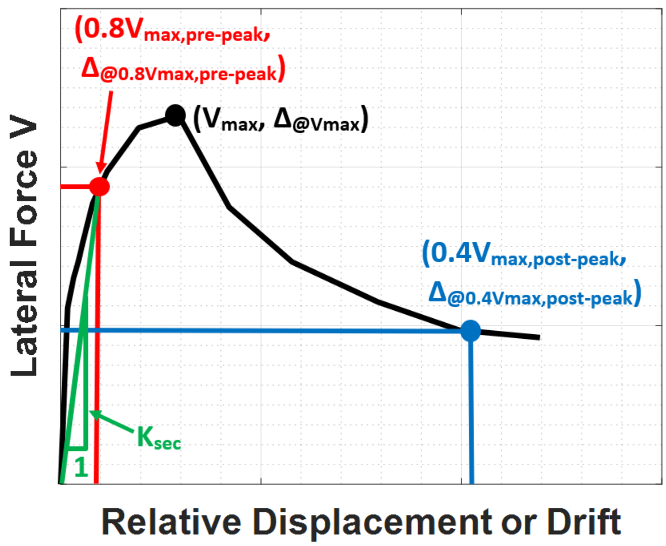


Figure 3.15 **Schematic defining key parameters compared amongst specimens in report: initial stiffness K_{sec}, drift at strength (drift capacity), relative drift at 80% lateral strength (pre-strength), and relative drift at 40% lateral strength (post-strength) from an envelope of the response.**

3.2.2.1 Existing Specimens

Two-Foot-Tall Specimens

Figure 3.16 shows the global drift at strength, defined herein as drift capacity, for all existing 2-ft-tall specimens, while Figure 3.17 shows the relative drift at strength, defined herein as relative drift capacity. Overall, the wet specimens achieved strength at lower drift amplitudes than the dry specimens. In terms of the relative displacement response, the wet specimens reached strength between 1.1% to 2.5% relative drift. The dry specimens achieved strength at 4.0% to 5.2% relative drift. The stucco over framing existing specimen had the lowest drift at strength of all exterior finishes tested, with an average global drift ratio of 2.0% and an average relative drift ratio of 1.2%. The stucco-only specimen had the earliest to peak in strength and the lowest drift capacity of all specimens tested. Figure 3.18 shows the relative drift at 80% pre-lateral strength, and Figure 3.19 shows the relative drift at 40% post-peak strength. The stucco-only specimen reached 40% residual strength at 4.5% relative drift on average, which was the earliest drift amplitude compared to any other specimen tested by over 3% relative drift. In addition, the stucco reached 80% of its strength by 0.5% relative drift. Stucco acts as a rigid body, and the furring nails attaching the stucco to the framing were only embedded 1/4 in. into the stucco. Due to this, the fasteners were fully mobilized at lower displacement amplitudes prior to their eventual detachment from the stucco. The detachment first occurred at the sill plate and bottom of the studs, which resulted in a sharp drop in strength; see Figure 3.20 where the relative hysteretic response of a stucco finished specimen overlays the relative hysteretic response a horizontal siding finished specimen. Likewise, an overlay of the hysteretic response of a stucco over horizontal sheathing specimen and a horizontal siding finished specimen is shown in Figure 3.21. The same large drop in strength was experienced by the stucco over horizontal sheathing finished cripple wall. This reduction, however, occurs around 3% to 4% relative drift rather than between about 1.5% to 2.5% relative drift. With the addition of the sheathing boards, the imposed displacement was shared between the sheathing fasteners and the furring nails, which increased the drift capacity of the specimen significantly. Figure 3.20 compares the stucco over horizontal sheathing versus and horizontal siding specimens. Even after the large drops of strength that occur in the drift cycles following peak strength, the stucco over horizontal sheathing specimen still maintained more strength than the horizontal siding specimen. When the monotonic push was implemented, the residual strength of the two specimens was similar, showing that the sheathing and siding boards were the only finish material providing lateral resistance.

While the drift capacity of the horizontal siding specimen was larger than any of the exterior finishes tested, the lateral strength was dramatically lower. The drift capacity of the T1-11 finished cripple wall and the stucco over horizontal sheathing finished cripple wall was similar to each other. The relative drift at 40% post-peak strength was 7.7% for the stucco over horizontal sheathing finished specimen and 8.0% for the T1-11 finished specimen; however, the T1-11 finished specimen reached strength at nearly twice the relative drift ratio of the stucco over horizontal sheathing specimen (4.7% versus 2.4% relative drift ratio). All specimens with diagonal sheathing finish materials were not included in Figure 3.19 due to their residual strength being a consequence of anchor bolt fractures of sill plate cracks. The relative drift ratio at 40% post-peak strength was less than their relative drift ratio at lateral strength because majority of the imposed displacement was accumulated by the displacement of the sill plate relative to the foundation.

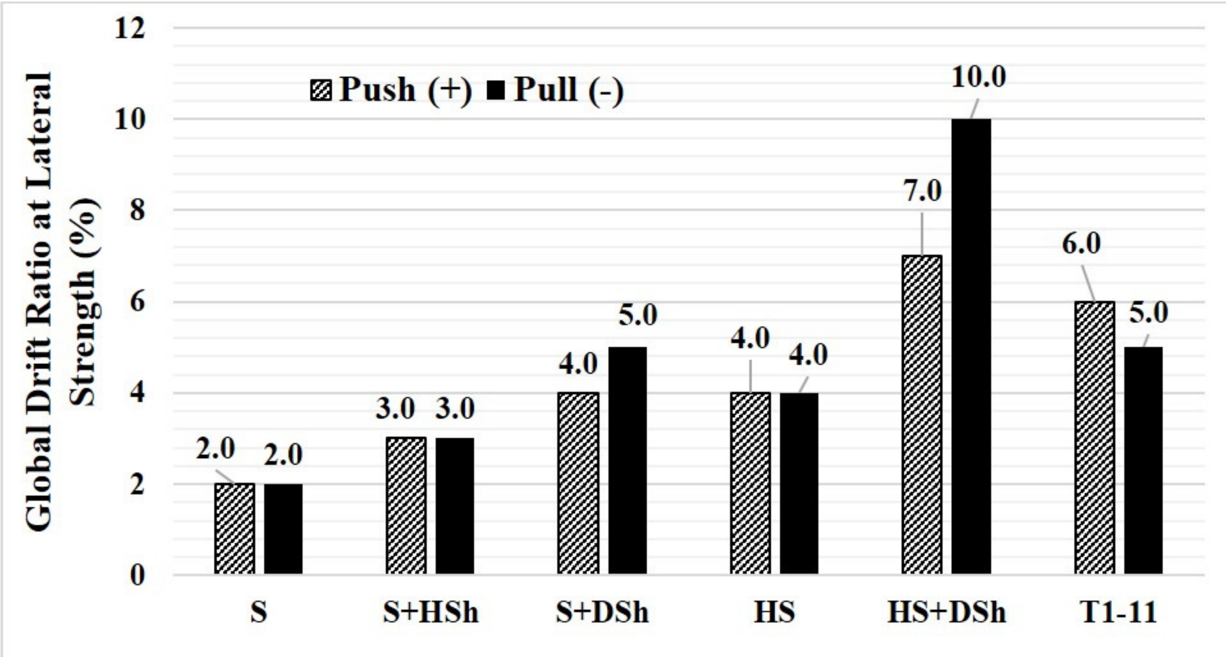


Figure 3.16 Comparison of *global* drift at strength of existing 2-ft-tall cripple walls with various exterior finishes.

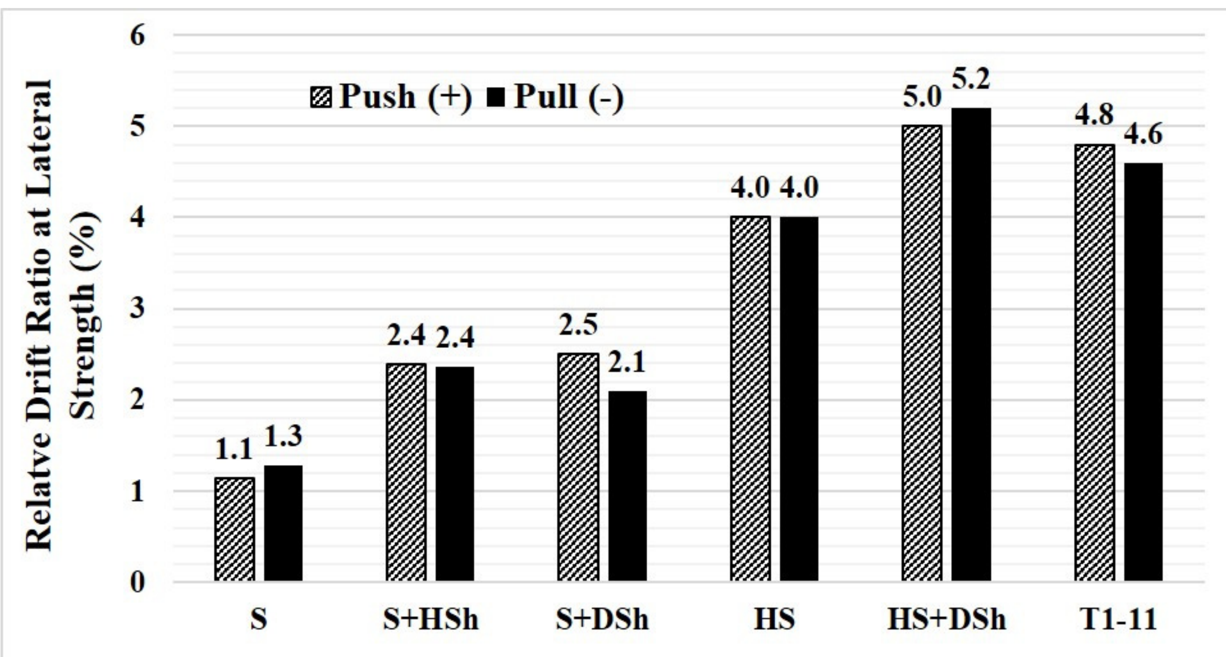


Figure 3.17 Comparison of *relative* drift at strength of existing 2-ft-tall cripple walls with various exterior finishes.

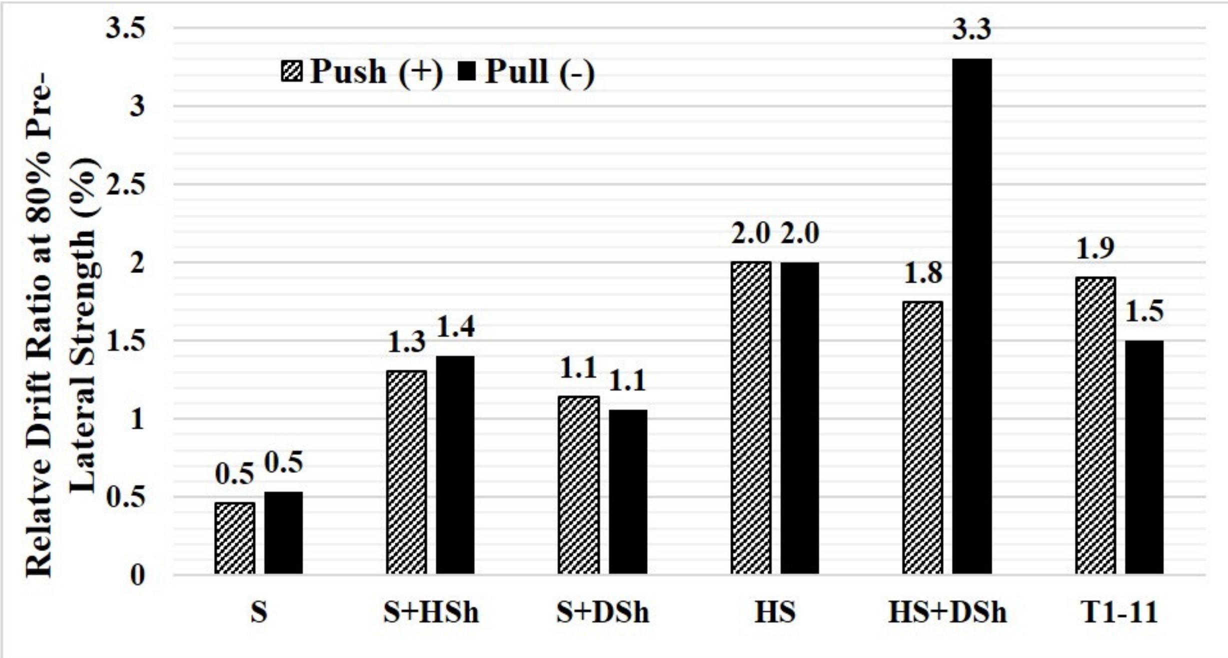


Figure 3.18 Comparison of *relative* drift at 80% pre-lateral strength of the existing 2-ft-tall cripple walls with various exterior finishes.

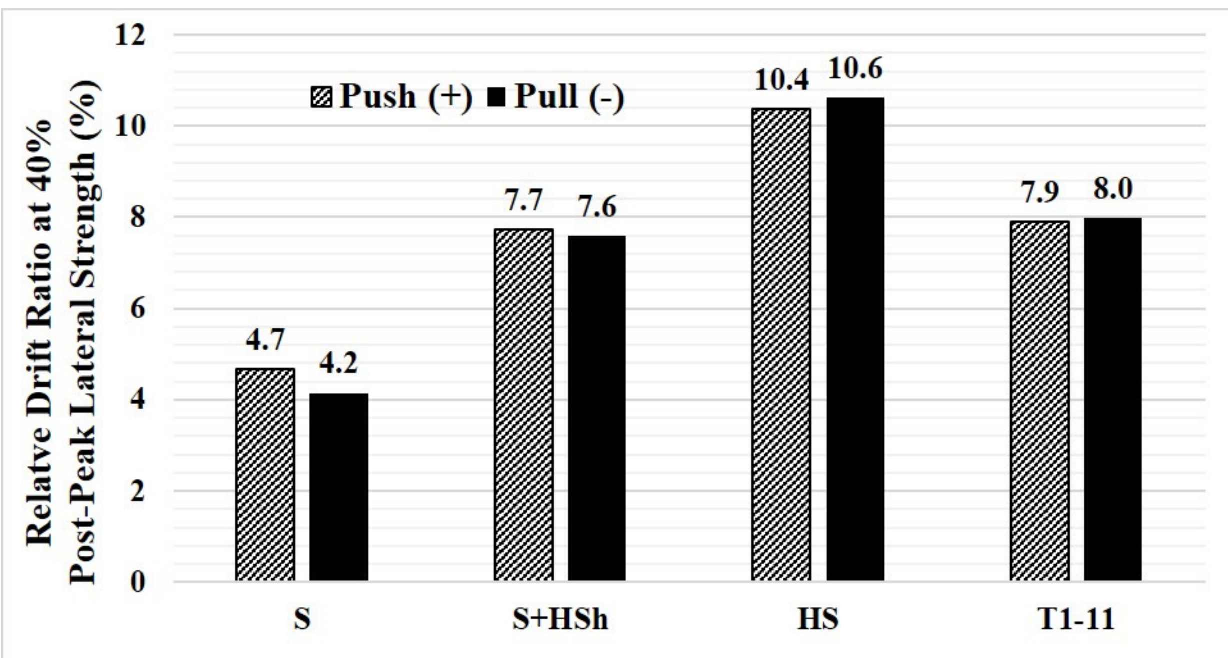


Figure 3.19 Comparison of *relative* drift at 40% post-peak strength of the existing 2-ft-tall cripple walls with various exterior finishes.

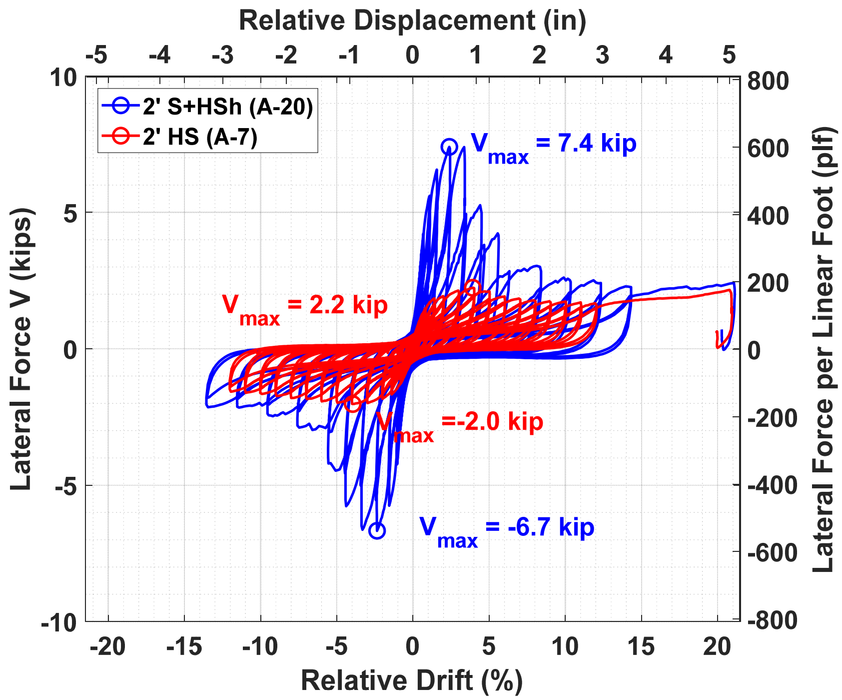


Figure 3.20 Lateral force versus relative lateral drift and displacement hysteresis of the existing 2-ft-tall specimens with stucco over horizontal sheathing and horizontal siding exterior finishes.

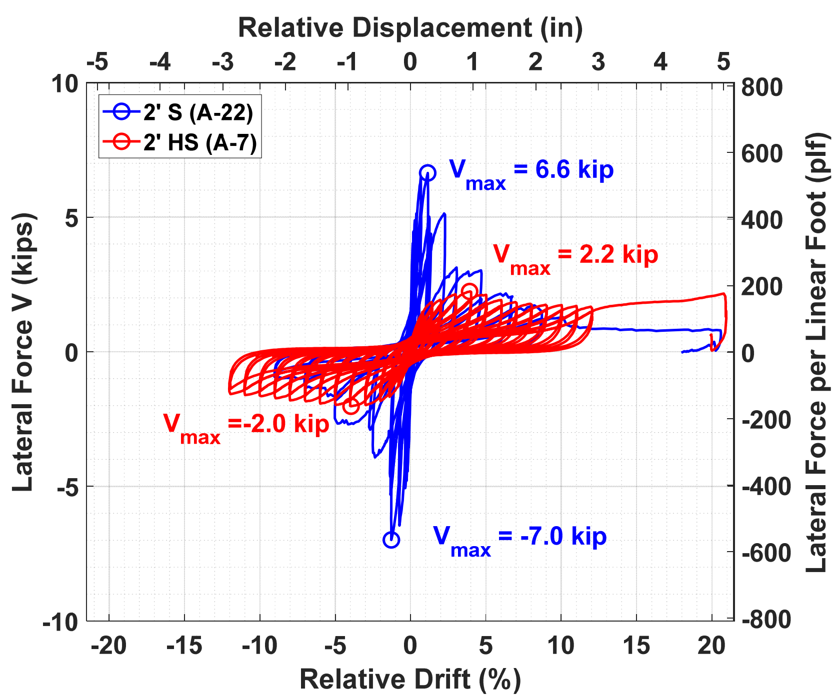


Figure 3.21 Lateral force versus relative lateral drift and displacement hysteresis of the existing 2-ft-tall specimens with stucco and horizontal siding exterior finishes.

Existing Six-Foot-Tall Specimens

Figure 3.22 shows the global drift at strength for all existing 6-ft-tall specimens, and Figure 3.23 shows the relative drift at strength. Overall, the existing stucco finished specimen achieved strength at lower displacement amplitudes compared to the dry specimens. In terms of the relative displacement response, the existing stucco finished specimens reached strength at 1.1% relative drift on average. For the T1-11 finished specimen, strength was achieved on average at 2.5% relative drift. Both these responses were in stark contrast to the response of the existing horizontal siding finished cripple wall, which did not reach strength until 11.5% relative drift. Figure 3.26 is an overlay of the relative hysteretic response of stucco finished and horizontal siding finished specimens. While the stucco finished specimen reached strength at early displacement amplitudes and quickly loss strength in the following displacement cycles, the horizontal siding specimen continued to gain strength throughout the entire test. Figure 3.24 shows the relative drift at 80% pre-lateral strength, and Figure 3.25 shows the relative drift at 40% pre-peak strength. These figures demonstrate that the drift capacities of the stucco finished specimen and T1-11 finished cripple walls were similar. The T1-11 finished cripple wall reached strength at a lower displacement amplitude, but the stucco finish cripple wall retained its strength for slightly longer, as indicated by this specimen attaining a 60% drop in strength at 7.1% relative drift, while the same occurred for the T1-11 specimen at 6.1% relative drift.

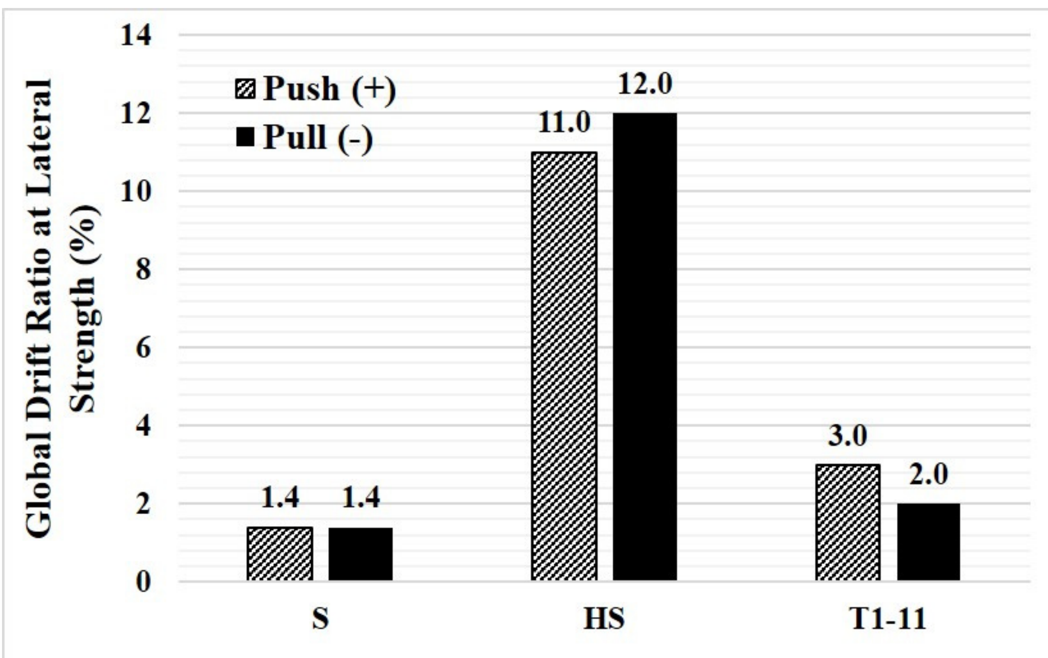


Figure 3.22 Comparison of *global* drift at strength of the existing 6-ft-tall cripple walls with various exterior finishes.

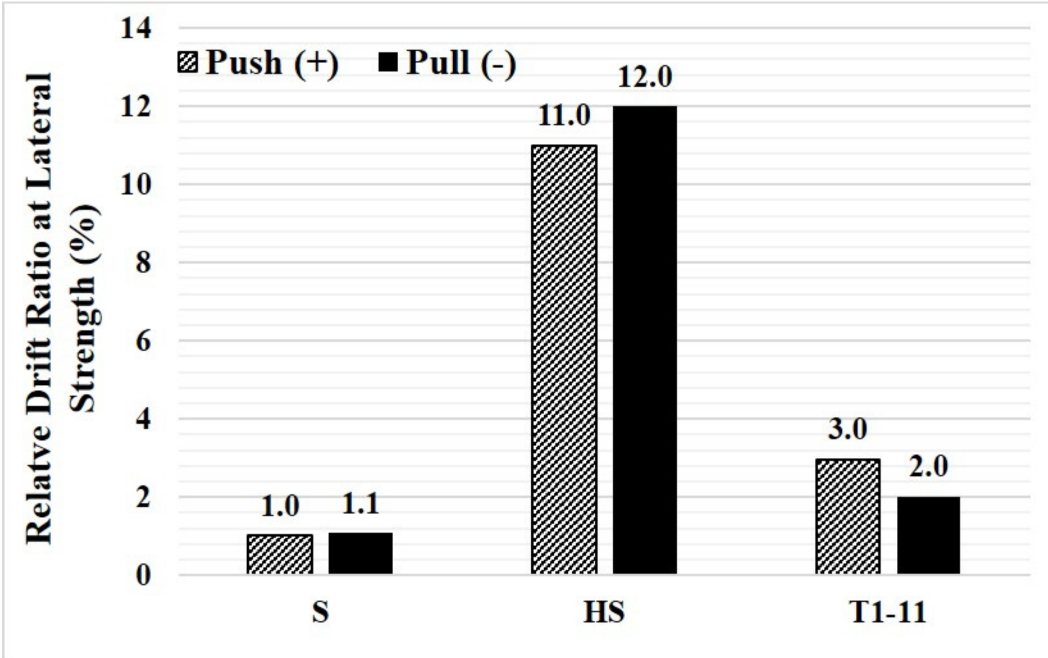


Figure 3.23 Comparison of *relative* drift at strength of the existing 6-ft-tall cripple walls with various exterior finishes.

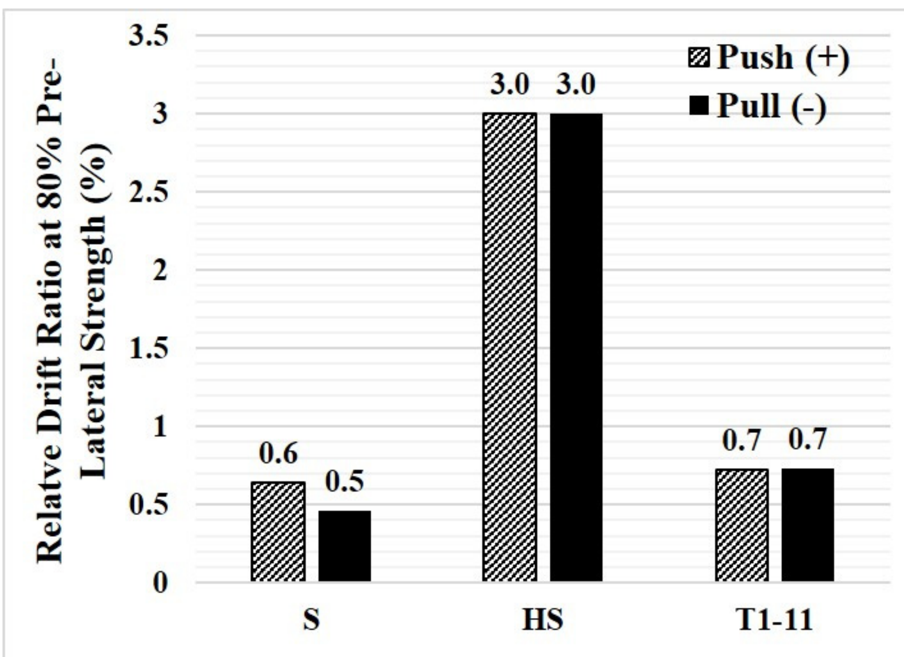


Figure 3.24 Comparison of *relative* drift at 80% pre-lateral strength of the existing 6-ft-tall cripple walls with various exterior finishes.

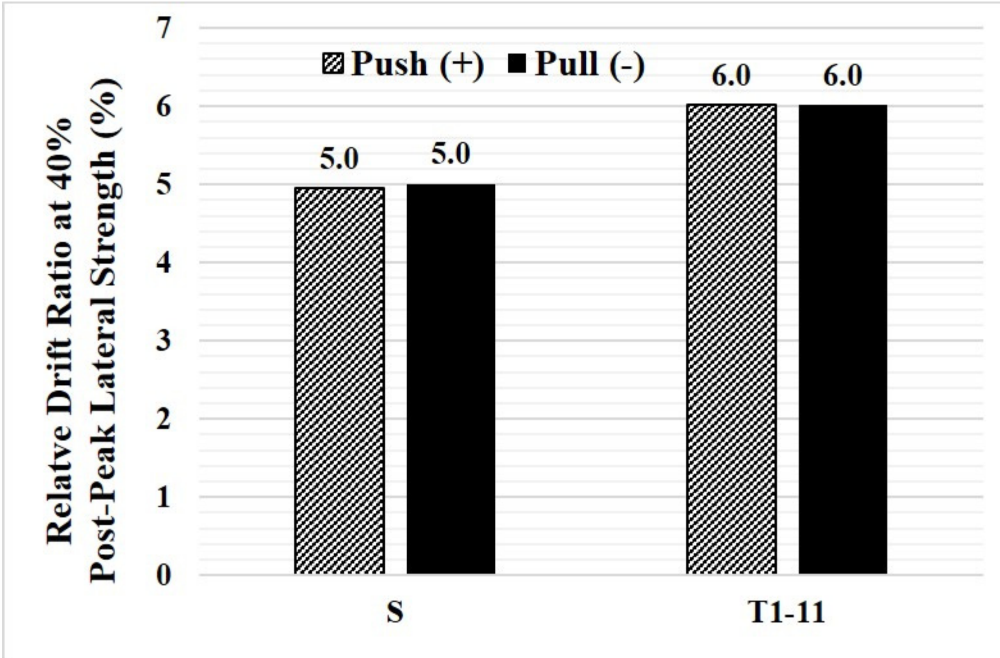


Figure 3.25 Comparison of *relative* drift at 40% post-peak strength of the existing 6-ft-tall cripple walls with various exterior finishes.

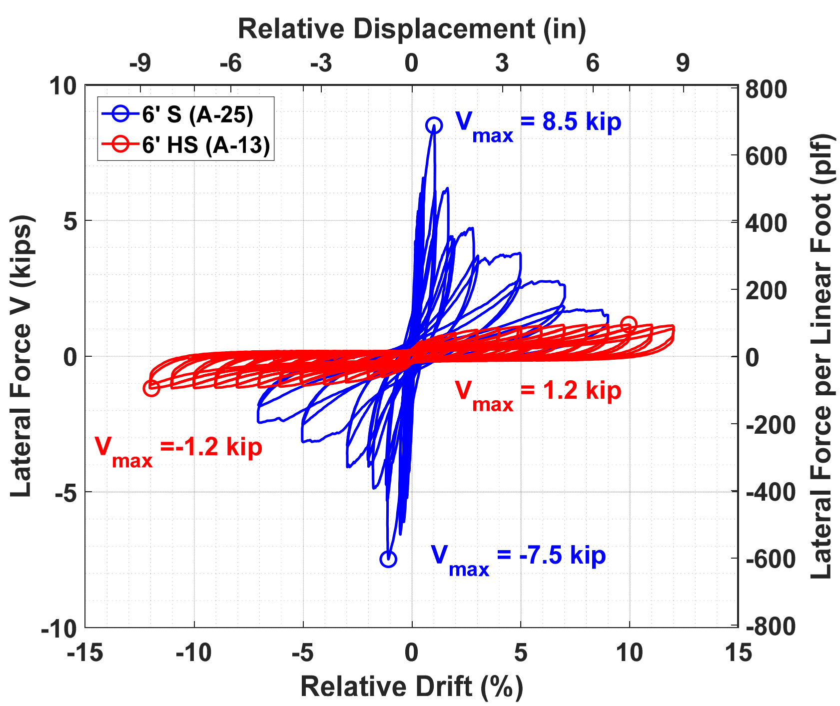


Figure 3.26 Lateral force versus relative lateral drift and displacement hysteresis of the existing 6-ft-tall specimens with stucco and horizontal siding exterior finishes.

3.2.2.2 Retrofitted Specimens

Retrofitted Two-Foot-Tall Specimens

Figure 3.27 shows the drift capacity for all retrofitted 2-ft-tall specimens, and the relative drift capacity is shown in Figure 3.28. The relative drift at 80% pre-lateral strength is given in Figure 3.29, and the relative drift at 40% post-peak strength is shown in Figure 3.30. With the addition of the retrofit, the drift capacities of the wet and dry specimens were much closer compared to the existing 2-ft-tall specimens. If the specimens with diagonal sheathing are omitted, the drift capacities of the remaining specimens are nearly the same. All specimens reached strength between 4.7% and 6.1% relative drift ratio and 40% post-peak strength between 9.3% and 10.5% relative drift ratio. The horizontal siding finished specimen reached strength and 40% residual strength at later drift amplitudes than any other specimen, 6.1% and 10.5%, respectively. For the stucco over horizontal sheathing and T1-11 finished cripple walls, the ranges of these values narrowed to between 4.7% and 5.3% relative drift ratio and between 9.3% and 9.6% relative drift ratio. In Figure 3.31, an overlay of the relative hysteretic response of the stucco finished and horizontal siding finished specimens is shown. Figure 3.32 shows the overlay for the stucco over horizontal sheathing finished and horizontal siding finished specimens. The stucco finished specimens reached strength at an earlier displacement amplitude, but overall, the responses were similar. Based on the similarity between the responses, it is evident that regardless of the exterior finish materials, the addition of the retrofit dominated the response.

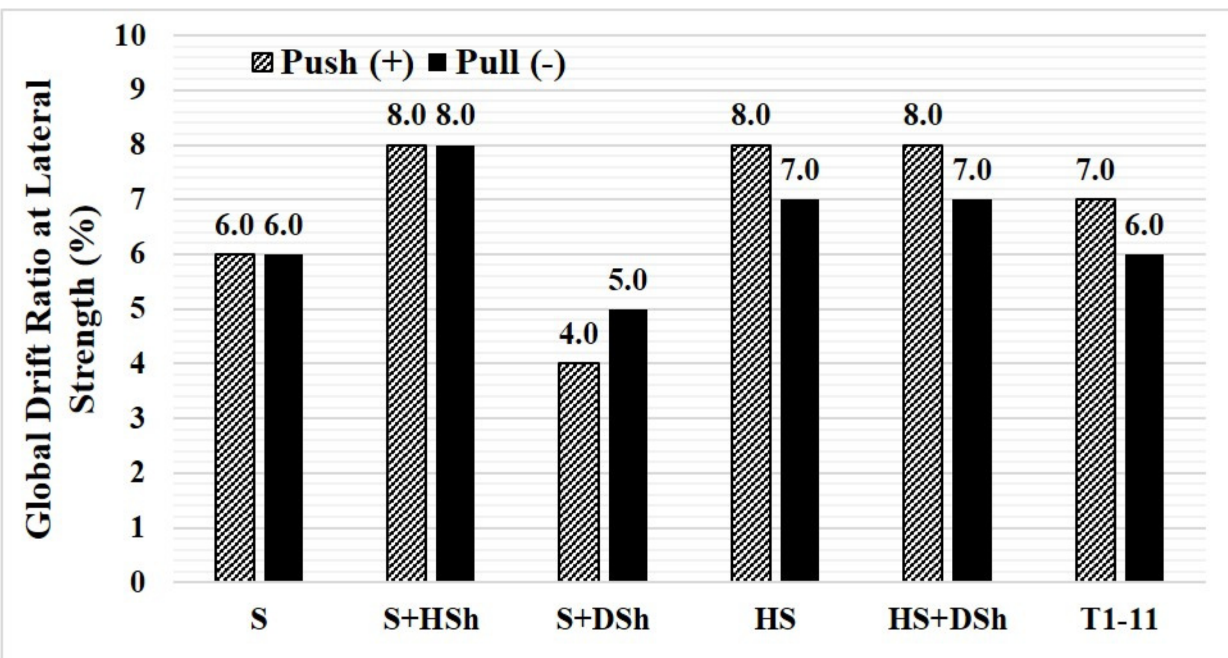


Figure 3.27 Comparison of *global* drift at strength of the retrofitted 2-ft-tall cripple walls with various exterior finishes.

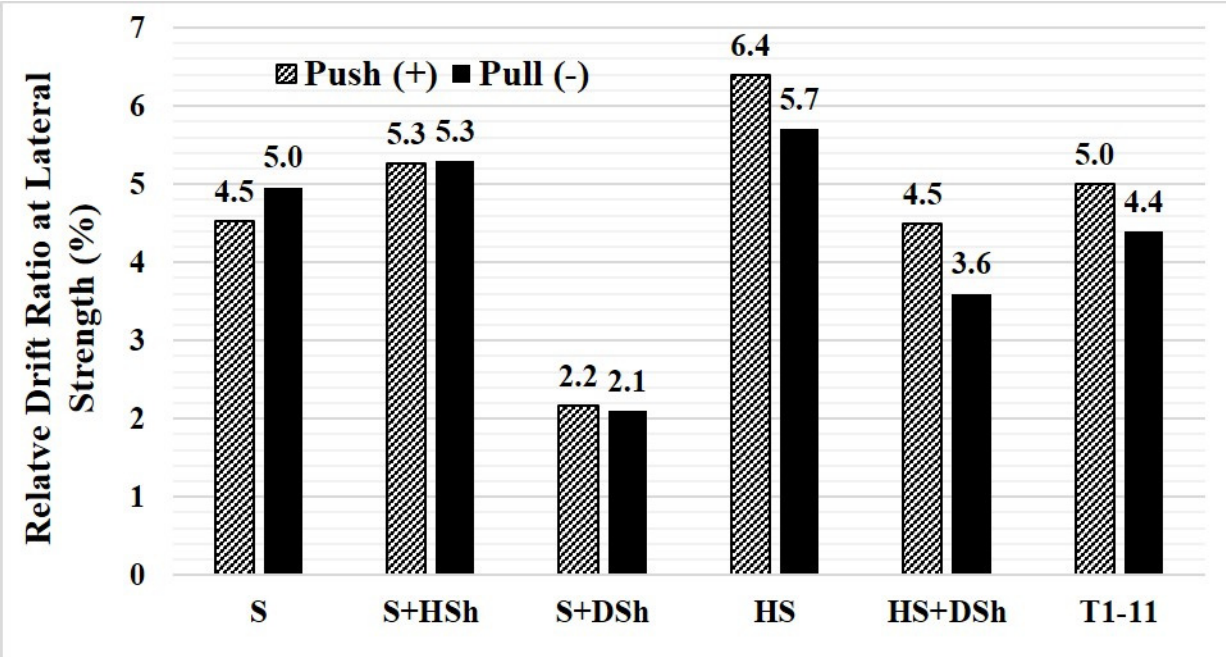


Figure 3.28 Comparison of *relative* drift at strength of the retrofitted 2-ft-tall cripple walls with various exterior finishes.

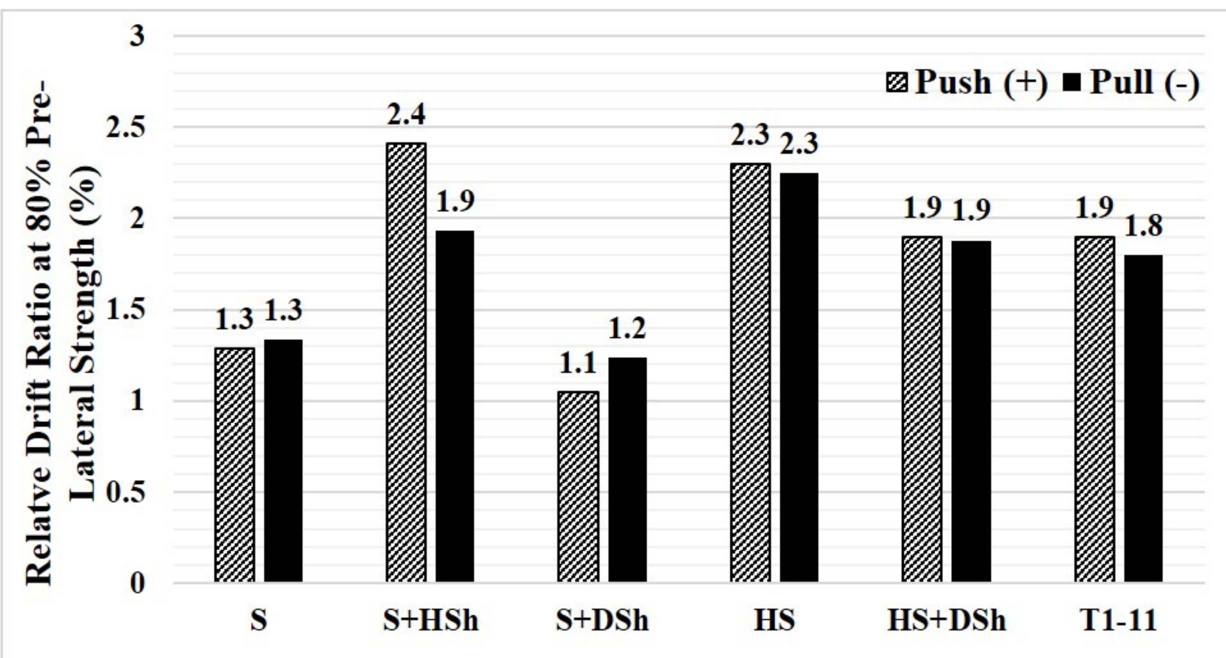


Figure 3.29 Comparison of *relative* drift at 80% pre-lateral strength of the retrofitted 2-ft-tall cripple walls with various exterior finishes.

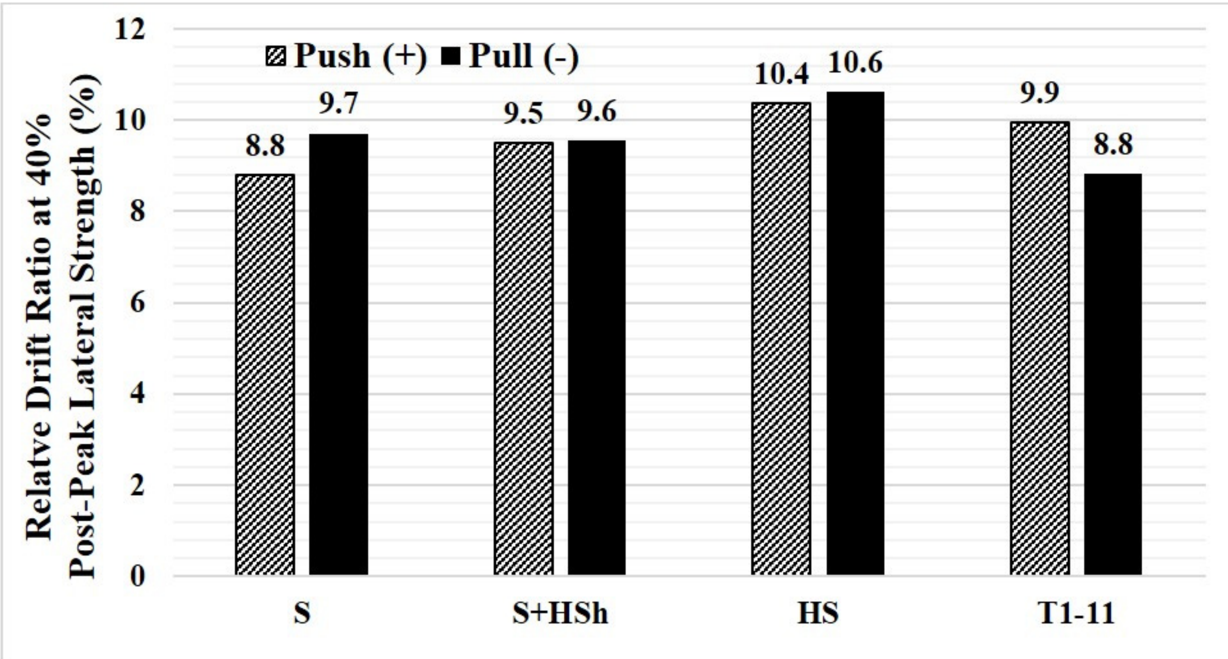


Figure 3.30 Comparison of *relative* drift at 40% post-peak strength of the retrofitted 2-ft-tall cripple walls with various exterior finishes.

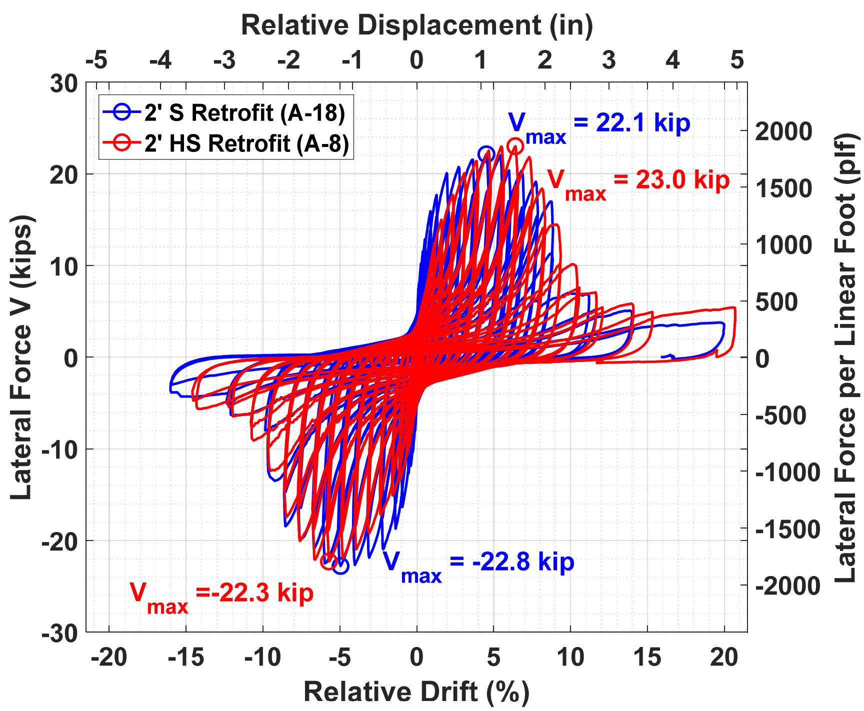


Figure 3.31 Lateral force versus relative lateral drift and displacement hysteresis of the retrofitted 2-ft-tall specimens with stucco and horizontal siding exterior finishes.

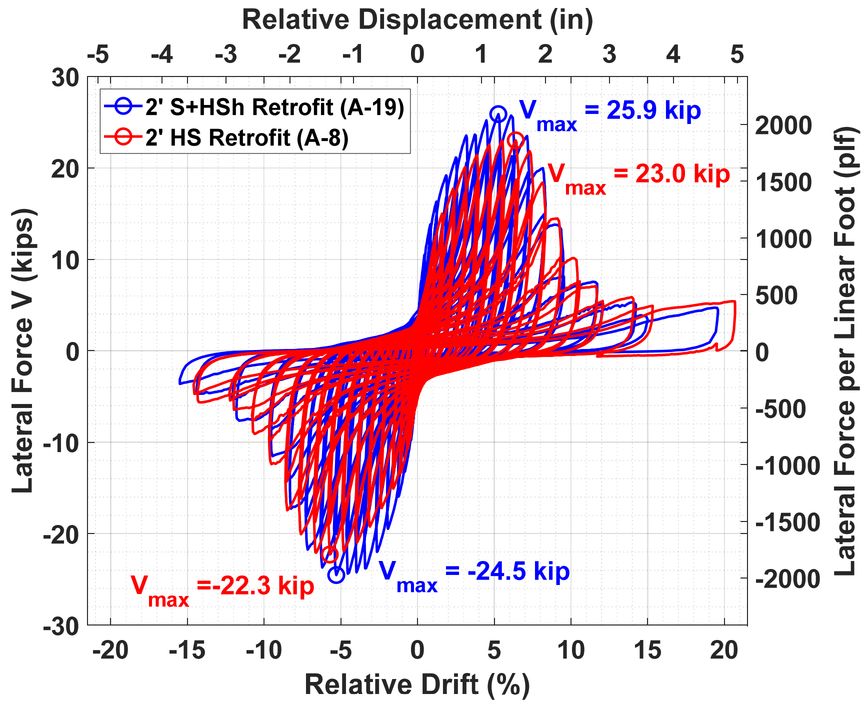


Figure 3.32 **Lateral force versus relative lateral drift and displacement hysteresis of the retrofitted 2-ft-tall specimens with stucco over horizontal sheathing and horizontal siding exterior finishes.**

Six-Foot-Tall Specimens

Figure 3.33 shows the drift capacity for all retrofitted 6-ft-tall specimens, and the relative drift capacity is shown in Figure 3.34. The relative drift at 80% pre-lateral strength is given in Figure 3.35, and the relative drift at 40% post-peak strength is shown in Figure 3.36. Similar to the 2-ft-tall specimens, the addition of the retrofit resulted in the drift capacities of the wet and dry finished cripple walls being much closer compared to the existing 6-ft-tall specimens. The horizontal siding over diagonal sheathing specimen attained strength at a later displacement cycle than the other two specimens with an average relative drift ratio 3.5%. The stucco finished cripple wall reached strength at 2.9% relative drift, and the T1-11 finished cripple wall reached strength at 2.5% relative drift. The stucco finished cripple wall had the largest drift capacity, losing 60% of strength at 7.0% relative drift. In addition, the stucco finished specimen gained strength at earlier displacement amplitudes compared to any of the other specimens. The cripple wall reached 80% pre-lateral strength by 1.0% relative drift whereas the horizontal siding specimen reached this point at 1.6% relative drift. Of the three specimens tested, the horizontal siding finished cripple wall had the lowest drift capacity.

Figure 3.37 shows an overlay of the relative hysteretic response for the stucco and horizontal siding specimens. While the responses are similar due to the retrofit dominating the response, the horizontal siding finished specimen observed a larger reduction in lateral load capacity in subsequent drift cycles compared to the stucco finished specimen. With the increased height of the cripple wall, more furring nails remained attached to the framing at larger displacement amplitudes than the 2-ft-tall specimen. Therefore, even at larger displacement amplitudes, the stucco finish still provided a significant amount of lateral resistance. The horizontal siding provided a small amount of resistance to begin with, so the larger drops in capacity after peak are indicative of the plywood detaching from the framing. By the end of the test, most of the resistance provided was due to the horizontal siding.

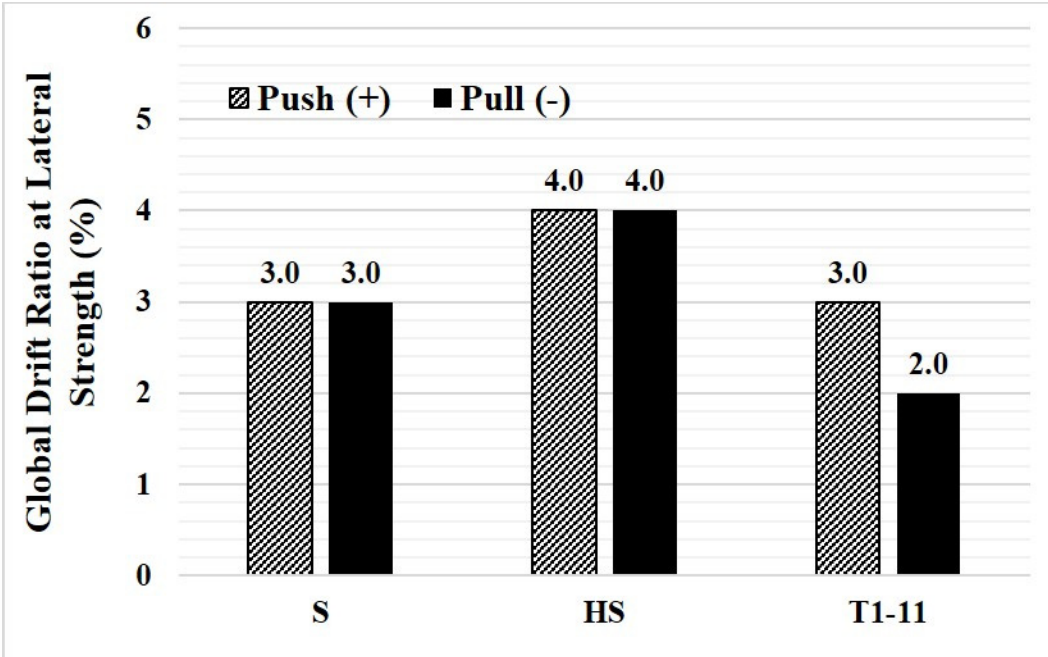


Figure 3.33 Comparison of *global* drift at strength of the retrofitted 6-ft-tall cripple walls with various exterior finishes.

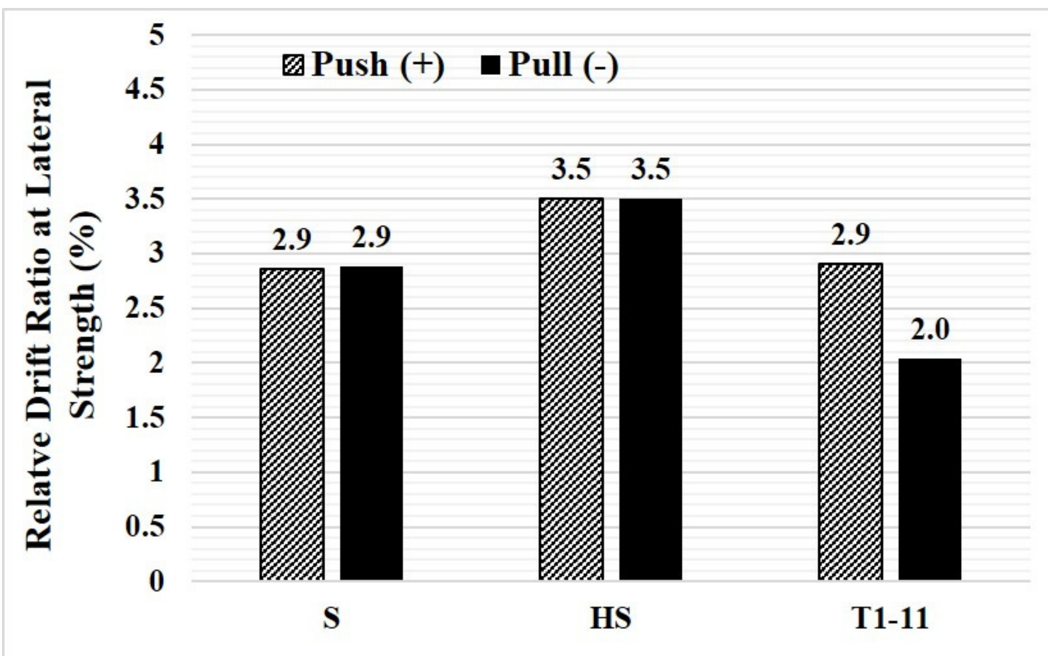


Figure 3.34 Comparison of *relative* drift at strength of the retrofitted 6-ft-tall cripple walls with various exterior finishes.

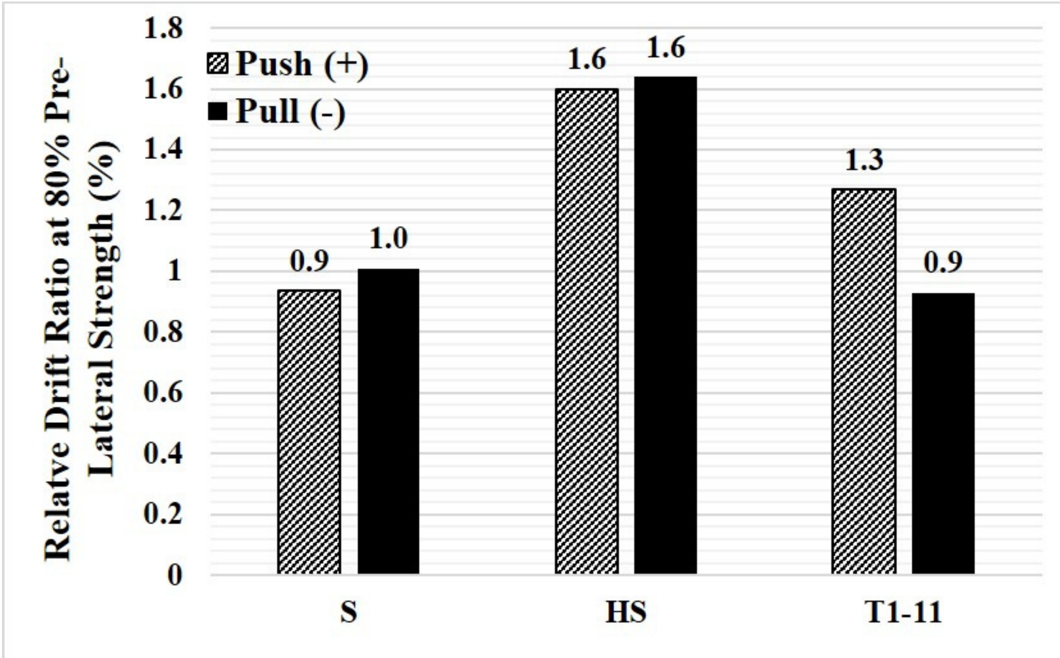


Figure 3.35 Comparison of *relative* drift at 80% pre-lateral strength of the retrofitted 6-ft-tall cripple walls with various exterior finishes.

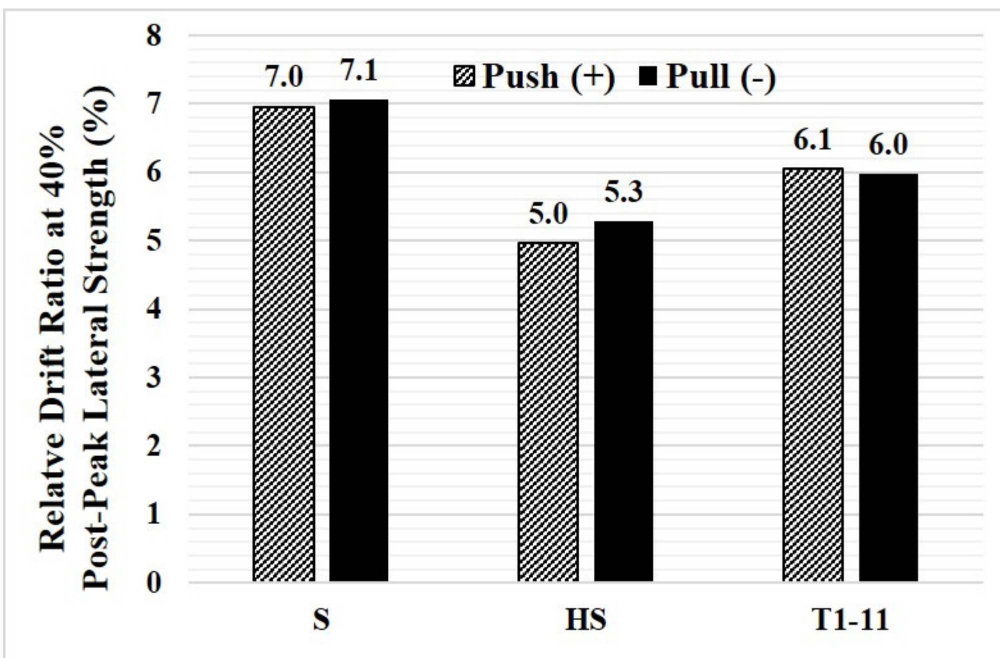


Figure 3.36 Comparison of *relative* drift at 40% post-peak strength of the 6-ft-tall cripple walls with various exterior finishes: (a) existing specimens; and (b) retrofitted specimens.

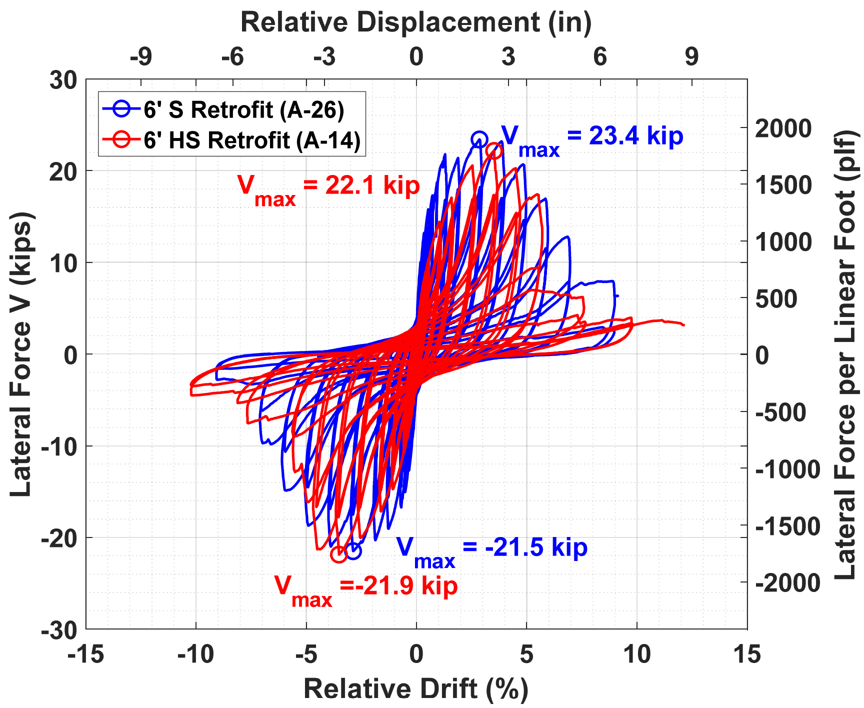


Figure 3.37 **Lateral force versus relative lateral drift and displacement hysteresis of the retrofitted 6-ft-tall specimens with stucco and horizontal siding exterior finishes.**

3.2.3 Initial Stiffness K_{sec}

3.2.3.1 Existing Specimens

Two-Foot-Tall Specimens

As shown in Figure 3.15, the initial stiffness is defined as the secant stiffness associated with 80% pre-lateral strength. Figure 3.38 shows the initial stiffness for the existing 2-ft-tall cripple walls with all exterior finishes tested. Of the six specimens, the stucco finished cripple wall had the highest secant stiffness which was 57.7 kip/in on average between push and pull loading. The initial stiffness of the stucco finished cripple wall was over 135% larger than the stiffest dry specimen (horizontal siding over diagonal sheathing finished cripple wall). The horizontal siding over diagonal sheathing finished specimen had 50% of the average secant stiffness of the stucco over diagonal sheathing finished specimen. The diagonal sheathing was the second stiffest finish material tested, but it was significantly lower in stiffness than stucco. When the stucco overlaid a sheathing material, there was a large decrease in the stiffness of the specimen. For example, the stucco finished specimen's average initial stiffness was 165% stiffer larger than the stucco over horizontal sheathing finished specimen. This reduction in stiffness could be attributed to the decreased rigidity of the connection of the stucco. When the stucco was fastened directly to the framing, all of the imposed displacement was carried by the furring nails, whereas in the presence of a layer of sheathing material between the stucco and the framing, much of the imposed displacement was taken on by the fasteners attaching the sheathing to the framing. The most flexible specimen was the horizontal siding finished cripple wall. The average initial stiffness of this specimen was 18% of the average initial stiffness of the stucco finished specimen. The T1-11 exterior finish was also significantly more flexible than the stucco finished specimen, with an average initial stiffness less than 25% of the average initial stiffness of the stucco finished specimen.

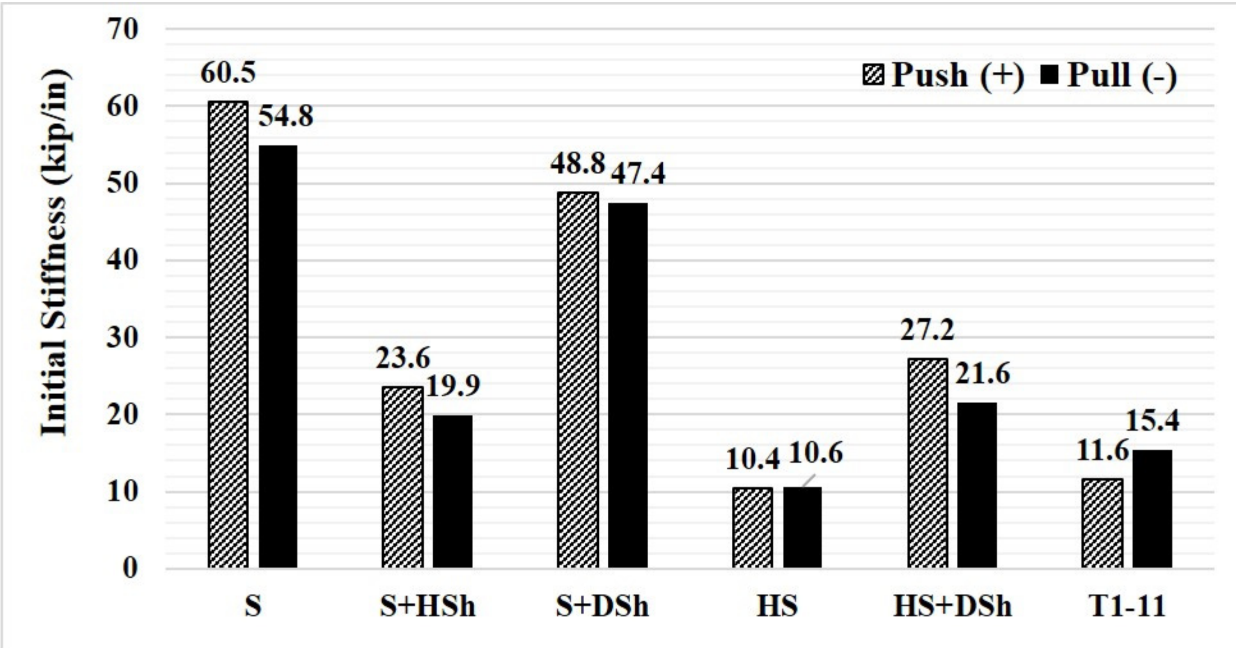


Figure 3.38 **Comparison of initial stiffness for *relative* drift at 80% pre-lateral strength of existing 2-ft-tall cripple walls with various exterior finishes.**

Six-Foot-Tall Specimens

Figure 3.39 shows the initial stiffness for the existing 6-ft-tall specimens. Once again, the stucco finish cripple wall was the stiffest of the exterior finishes tested. The average initial stiffness was 20.5 kip/in., which was over 45 times stiffer compared to the horizontal siding finished cripple wall. The 6-ft-tall horizontal siding finished cripple wall was the most flexible cripple wall tested in the entire program by a significant amount. The average initial stiffness of its 2-ft-tall counterpart was over 23 times higher. The T1-11 finished cripple wall was over 15 times stiffer than the horizontal siding finished cripple wall, while it was around one-third as stiff as the stucco finished cripple wall.

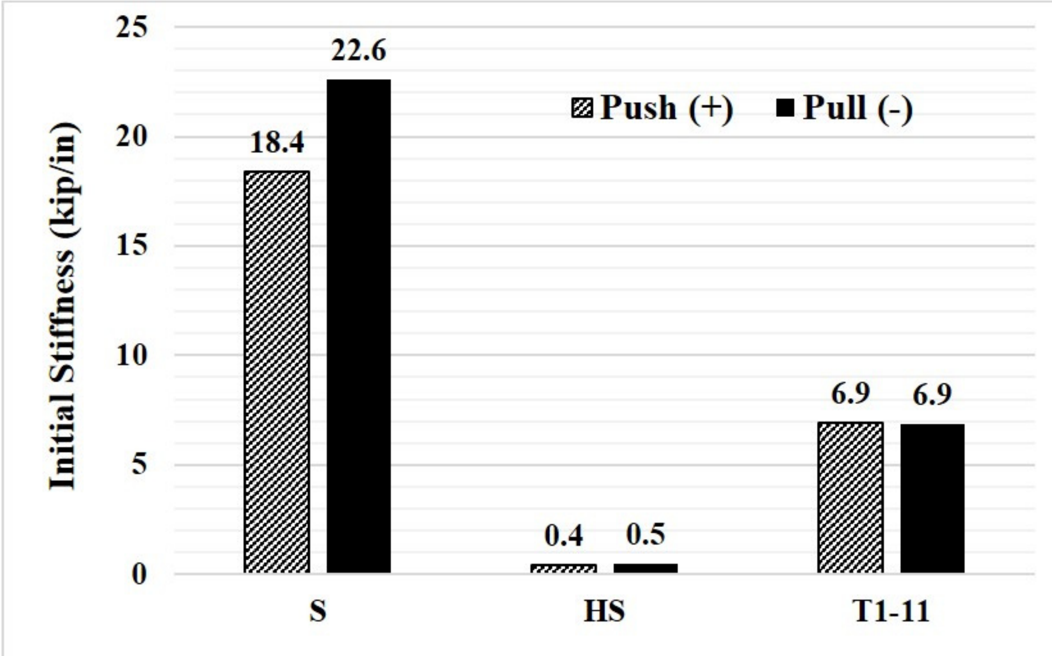


Figure 3.39 **Comparison of initial stiffness for *relative* drift at 80% pre-lateral strength of existing 6-ft-tall cripple walls with various exterior finishes.**

3.2.3.2 Retrofitted Specimens

Two-Foot-Tall Specimens

Figure 3.40 shows the percent increase in initial stiffness for the retrofitted 2-ft-tall specimens compared with the existing 2-ft-tall specimens with all six exterior finishes, and Figure 3.41 show the initial stiffness for the retrofitted 2-ft-tall cripple walls. As with the existing specimens, the wet finished specimens had larger initial stiffnesses compared to the dry finished specimens. The only exception was for the case of the horizontal siding over diagonal sheathing finished specimen, with an average initial stiffness 12% higher than the stucco over horizontal sheathing finished specimen. The stucco over diagonal sheathing specimen was the stiffest of any cripple wall tested, with an average initial stiffness of 99.6 kip/in. This was nearly 40% larger than the next stiffest specimen, which was the stucco finished cripple wall. The stucco over horizontal sheathing finished cripple wall was the most flexible of the wet finished specimens, with an average initial stiffness of 48.9 kip/in. The stiffness of this specimen was almost 80% larger than the horizontal siding finished cripple wall and nearly double the stiffness of the T1-11 finished cripple wall, which was the most flexible of the retrofitted 2-ft-tall cripple walls tested. This is due to the configuration of the T1-11 finished cripple wall, with the material fastened to the framing and the edge nail specimen being 4 in. on center compared to 3 in. on center for the other retrofitted specimens.

The largest percent increase in stiffness attributed to the addition of the retrofit was for the horizontal siding finished cripple wall. The average initial stiffness increased by over 160% between both directions of loading. Both cripple walls with diagonal sheathing experienced over a 160% increase in initial stiffness in the pull direction of loading compared with around a 90% increase in the push direction of loading. The difference in increase could be attributed to the orientation of the diagonal sheathing boards. In the pull loading direction, the sheathing board would be put into tension, whereas in the push loading direction, the sheathing boards would experience compression. The lowest increase in stiffness due to the added retrofit was for the stucco over horizontal sheathing specimen which only increased, on average, 37% between both directions of loading.

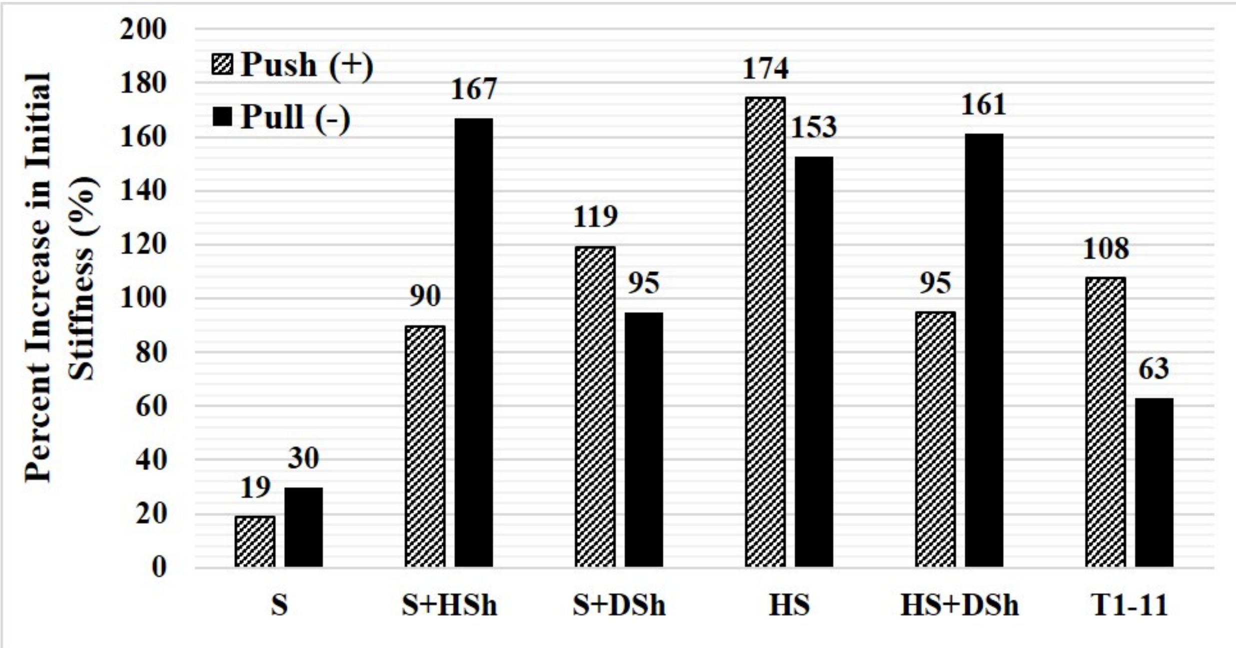


Figure 3.40 **Contribution of the retrofit to initial stiffness for relative drift at 80% pre-strength for all 2-ft-tall specimens with various exterior finishes.**

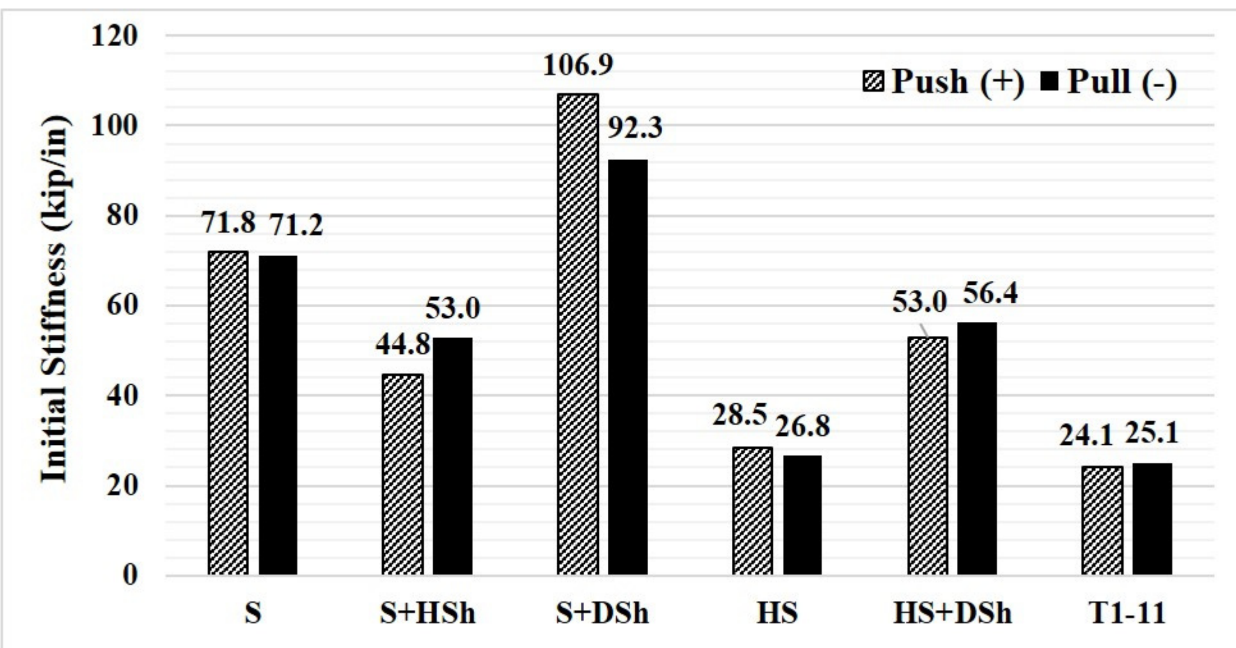


Figure 3.41 **Contribution of the retrofit to initial stiffness for relative drift at 80% pre-strength for all 2-ft-tall specimens with various exterior finishes.**

Six-Foot-Tall Specimens

Figure 3.42 shows the percent increase in initial stiffness for the retrofitted 6-ft-tall cripple walls with the three exterior finishes compared with their existing counterparts. Figure 3.43 provides the initial stiffness of the retrofitted 6-ft-tall specimens. As with the existing specimens, the stucco finished cripple wall was by far the stiffest of the cripple walls tested. The average initial stiffness of the stucco finished specimen was 32.2 kip/in. between both directions of loading. This was over 125% larger than the average initial stiffness of the horizontal siding finished cripple wall. The most flexible of the retrofitted specimens was the T1-11 finished cripple wall, with an average initial stiffness of 10.6 kip/in., or about one-third of the stiffness of the stucco finished cripple wall. As with the retrofitted 2-ft-tall specimens, the T1-11 finished 6-ft-tall specimen was the most flexible cripple wall due to the edge nail spacing and lack of plywood being fastened to the interior of the framing. By far, the largest relative increase in stiffness was for the horizontal siding finished specimen. The average initial stiffness was 31 times higher for the retrofitted specimen. This observation is akin to the dramatic increase in strength for the horizontal siding finished specimen, which is significantly weaker and softer than all specimens tested in its unretrofitted configuration. The stucco finished cripple wall stiffness increased by 60%, and the T1-11 finished cripple wall stiffness increased by 55%, on average.

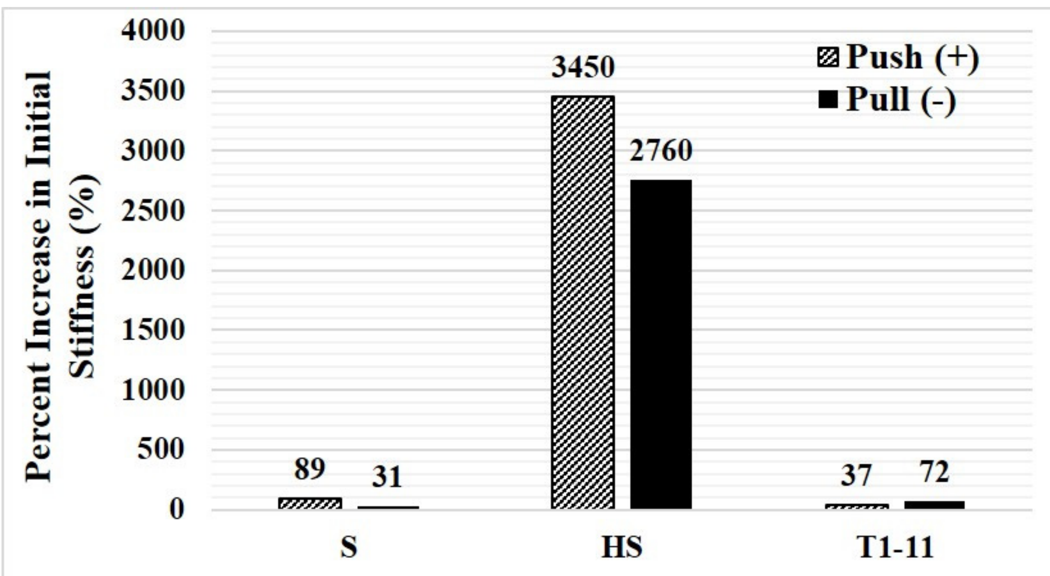


Figure 3.42 Contribution of the retrofit to initial stiffness for relative drift at 80% pre-strength for all 6-ft-tall specimens with various exterior finishes.

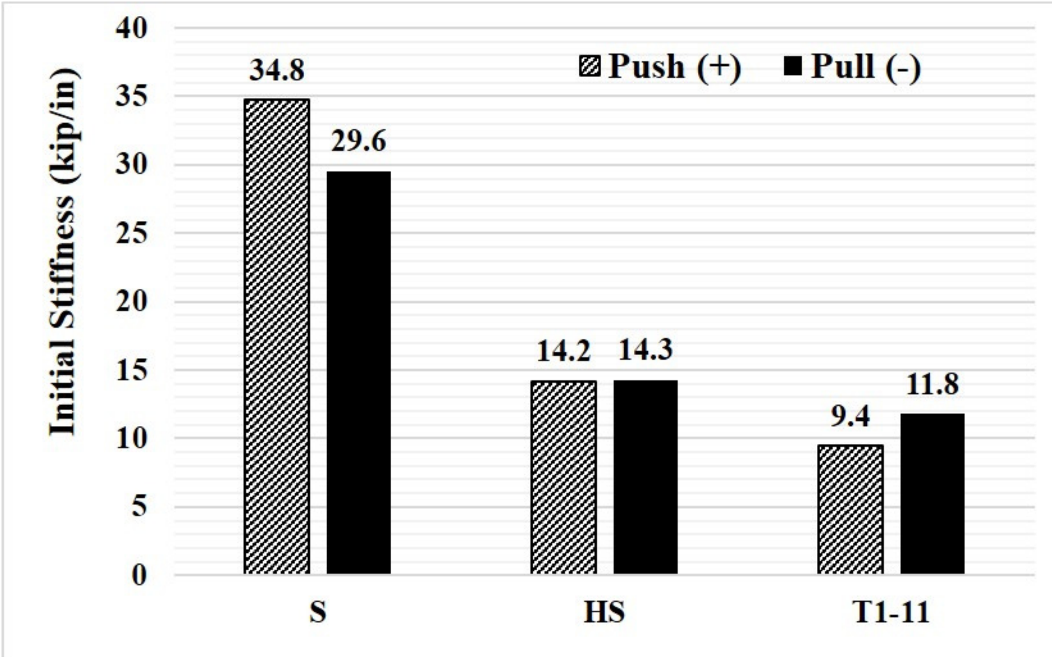


Figure 3.43 Comparison of initial stiffness for *relative* drift at 80% pre-lateral strength of the retrofitted 6-ft-tall cripple walls with various exterior finishes.

3.3 HYSTERETIC ENERGY DISSIPATION

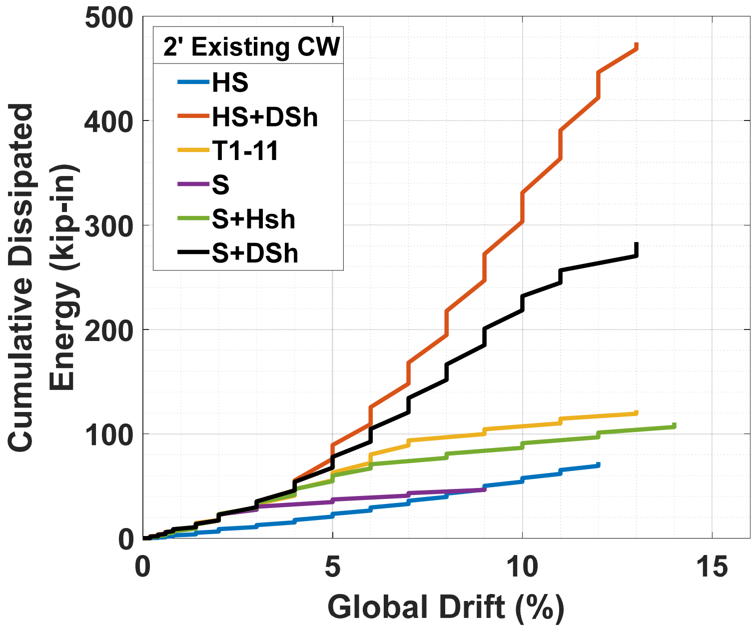
An important characteristic to describe the seismic resiliency of a cripple wall is the energy dissipated by the cripple wall during loading. Figure 3.44 through Figure 3.47 show various comparisons of the cumulative energy dissipated versus drift. The cumulative energy dissipated was calculated as the sum of area of the hysteretic loops in both push and pull loading for each cycle level group. The energy dissipated was calculated for both the leading and the trailing cycles in both the push and pull directions of loading. Both the relative and global responses are presented. These responses differed largely if the cripple wall slid on the foundation, as the friction between the sill plate and the foundation dissipates a significant amount of energy.

Figure 3.44 compares the cumulative energy dissipated for the existing 2-ft-tall cripple walls tested. The cripple walls containing diagonal sheathing dissipated the most energy of any of the specimens tested. By the end of the test, the horizontal siding over diagonal sheathing finished specimen dissipated over seven times as much energy as the horizontal siding finished specimen and nine times as much energy as the stucco finished specimen. Around 30% of the energy dissipated for the horizontal siding over diagonal sheathing and 50% of the energy dissipated for the stucco over diagonal sheathing finished specimen as in the form of the sill plate sliding along the foundation. Both specimens had little damage to their finishes relative to the other specimens tested due to both fracturing of the anchor bolts as well as cross-grain cracking of the sill plates. If the anchor bolts and sill plates had remained intact, the cumulative energy dissipation would have been significantly higher for both specimens. The cumulative energy dissipated by both specimens with diagonal sheathing was similar until around 4.5% relative drift ratio. By the end of the test, the stucco finished cripple wall had dissipated the least amount of energy, even though the strength of this specimen was over three times more than the horizontal siding finished specimen. This was largely due to the stucco finished cripple wall reaching strength at earlier drift amplitudes compared to the other cripple walls. The amount of energy dissipated by all specimens besides the horizontal siding finished cripple wall was nearly identical up to the 3% global drift ratio. After this point, the cumulative energy dissipation of the stucco finished specimen diverged due to a 60% drop in strength and the drift amplitude increasing to 2% for each subsequent drift cycle group. In terms of the global response, the stucco over horizontal sheathing finished cripple wall and the T1-11 finished cripple wall were nearly identical up to 5% drift. The strength of the stucco over horizontal sheathing specimen was larger than that of the T1-11 finished specimen, which increased the displacement between the sill plate and foundation that occurred during each drift cycle. Therefore, in terms of the relative response, the T1-11 finished cripple wall dissipated around 20% more energy than the stucco over horizontal sheathing specimen.

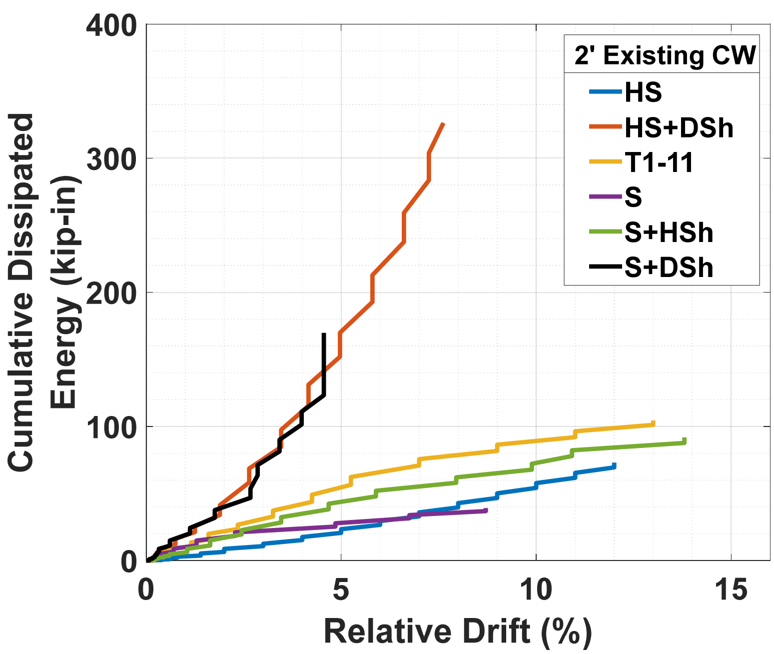
Figure 3.45 compares the cumulative energy dissipated for retrofitted 2-ft-tall cripple walls tested. Comparing the global response, the cumulative energy dissipated by the stucco over horizontal sheathing, stucco, and horizontal siding specimens were nearly identical up to 9% global drift ratio. The cumulative energy dissipated by all specimens besides the T1-11 finished cripple wall were consistent up to about 7% global drift. At this point, the cripple wall with the horizontal siding over diagonal sheathing finish began dissipating more energy per drift cycle group compared to all other specimens. In terms of the relative response, the cripple walls with diagonal sheathing began dissipating significantly more energy compared to all other specimens after around 2% relative drift. Both specimens lost strength due to anchor bolt fractures and sill plate cracks, as with the existing specimens, which caused a reduction in the energy dissipated during each cycle. Looking at the relative response, the subsequent drift cycles caused a reduction in relative drift for the specimen due to much of the imposed displacement being taken on by the displacement of the sill plate relative to the foundation. Up to around 2% relative drift, the wet finish specimens dissipated more energy than the dry finish specimens due to the rigidity of the stucco attachment. The T1-11 finished cripple wall dissipated the least amount of energy of any of the retrofitted specimens due to both the edge nail spacing being 4 in. on center instead of 3 in. on center as it was for the other retrofitted specimens, as well as the presence of only one material being fastened to the framing.

Figure 3.46 compares the cumulative energy dissipated for the existing 6-ft-tall cripple walls tested. The stucco cripple wall dissipated the most energy at every point during the test compared to all the other existing 6-ft-tall specimens. By 3% global drift, which was where the loading protocols of the tests varied, the stucco finished cripple wall had dissipated around 90% more cumulative energy than the T1-11 finished cripple wall and over 700% more energy than the horizontal siding finish cripple wall. The energy dissipated per drift cycle group was nearly equal for all drift cycle groups for the horizontal siding cripple wall.

Figure 3.47 compares the cumulative energy dissipated for retrofitted 6-ft-tall cripple walls tested. The stucco cripple wall dissipated the most energy at every point during the test than all retrofitted 6-ft-tall specimens. By 6% global drift, the point where the loading protocols of the tests diverged, the stucco finished cripple wall had dissipated around 10% more cumulative energy than the horizontal siding finished cripple wall and over 250% more energy than the T1-11 finished cripple wall. The T1-11 cripple wall dissipated the least amount of energy of the retrofitted 6-ft-tall cripple walls, which was again due to the edge nail spacing and only a single finish material being attached to the framing.



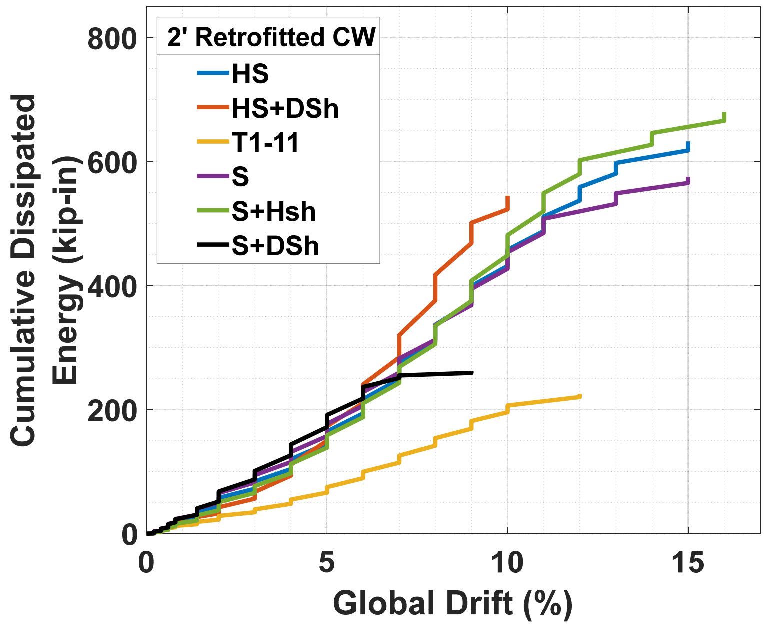
(a)



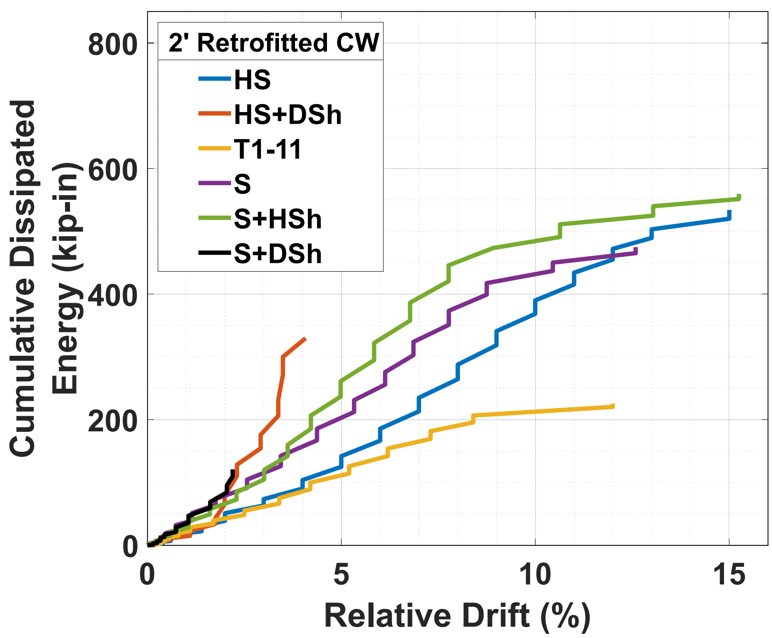
(b)

Figure 3.44 Retrofitted 2-ft-tall cripple wall, hysteretic energy dissipation comparison for various exterior finishes: (a) *global* response; and (b) *relative* response.

<u>**Legend:**</u> HS = horizontal siding; S = stucco only; HS+DSh = horizontal siding over diagonal sheathing; T1-11 = T1-11 wood structural panels; S+HSh = stucco over horizontal sheathing; S+DSh = stucco over diagonal sheathing.



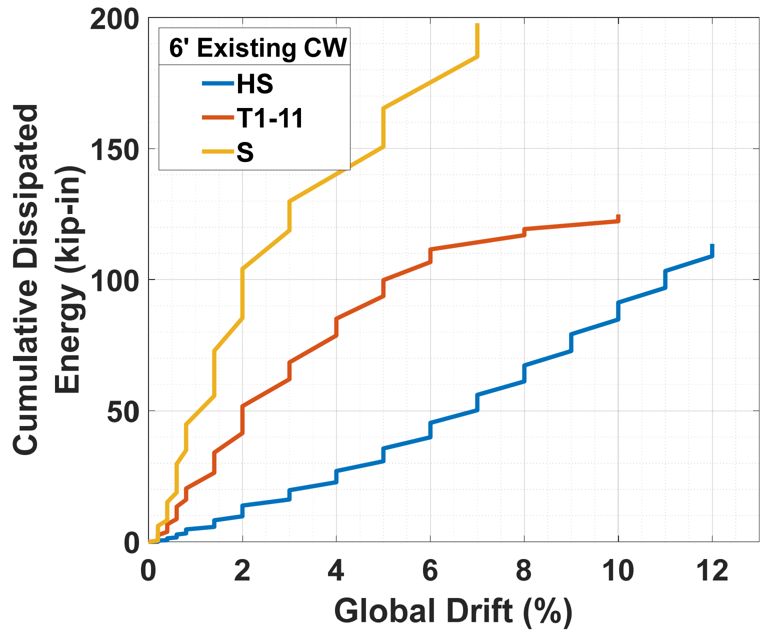
(a)



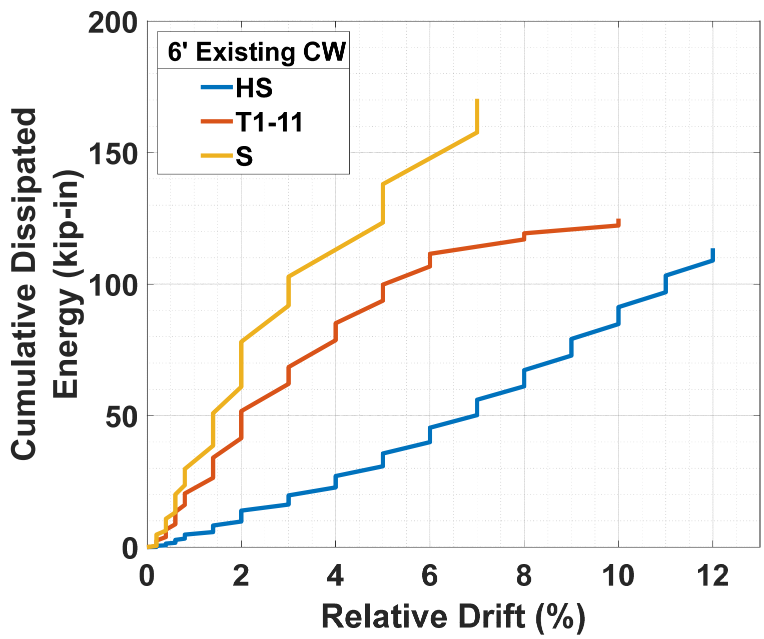
(b)

Figure 3.45 Retrofitted 2-ft-tall cripple wall, hysteretic energy dissipation comparison for various exterior finishes: (a) *global* response; and (b) *relative* response.

<u>**Legend:**</u> HS = horizontal siding; S = stucco only; HS+DSh = horizontal siding over diagonal sheathing; T1-11 = T1-11 wood structural panels; S+HSh = stucco over horizontal sheathing; S+DSh = stucco over diagonal sheathing.

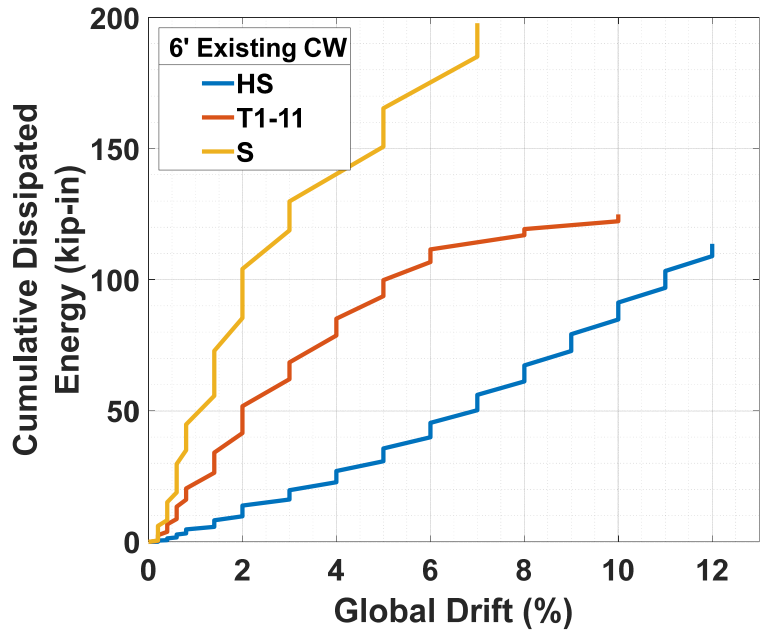


(a)

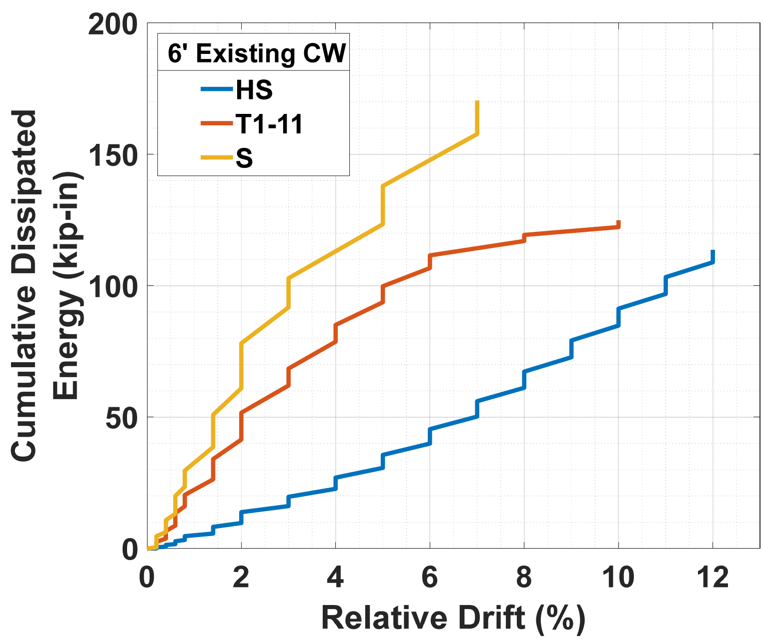


(b)

Figure 3.46 Existing 6-ft-tall cripple wall, hysteretic energy dissipation comparison for various exterior finishes: (a) *global* response; and (b) *relative* response.



(a)



(b)

Figure 3.47 Retrofitted 6-ft-tall cripple wall, hysteretic energy dissipation comparison for various exterior finishes: (a) *global* response; and (b) *relative* response.

4 Damage Observations

4.1 OVERVIEW

This chapter presents important differences in the physical damage characteristics observed amongst the different exterior finishes as they evolved during the cyclic testing. Tracking the physical damage of cripple walls is important in assessing the structural integrity of a cripple wall after a seismic event. Stucco cracking, stucco detachment from sheathing/framing, and sheathing nail withdrawal/rotations were consistently observed for wet finished specimens. Finish nail and plywood withdrawal/rotation, plywood panel tearing, and finish rotation were observed for dry finished specimens. Rotations as well as uplift and splitting of framing members were observed consistently for all specimens, regardless of finish type, though the severity of this type of damage varied. For retrofitted specimens, plywood nail withdrawal/pull through/rotation, panel tearing/crushing, and panel rotation were observed. The ability to relate the physical damage of a cripple wall to its lateral strength is key in determining what repairs are required to fix the aesthetic and structural elements of a cripple wall and the superstructure. Moreover, this information is useful for characterizing the fragility curves, part of the wider effort of the PEER–CEA project. To this end, this chapter is divided into sections based on the damage differences in observed damage at key drift ratios throughout the tests.

4.2 DAMAGE CHARACTERISTICS FROM 0.0% TO 1.4% DRIFT RATIO LEVEL (SERVICE-LEVEL DRIFT)

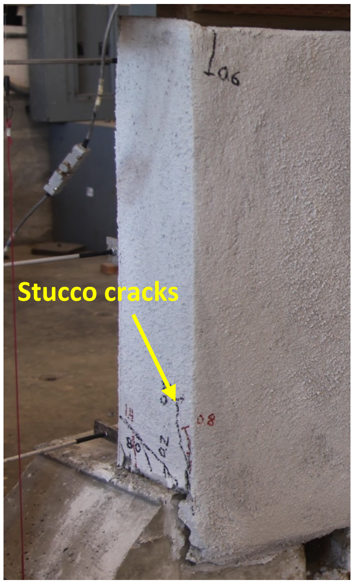
Understanding the physical damage characteristics of cripple walls at low-level drift amplitudes as the damage accrues is critical. Smaller amplitude drift demands are of particular value to assess the cost of repair if the dwelling remains serviceable. Herein, serviceability is a qualitative term loosely associated with damage so minor that the component would still readily allow the dwelling to serve its intended functionality, that is, safely remaining occupied. To this end, the imposed drift levels from the loading protocol of interest to the serviceability state are 0.2%, 0.4%, 0.6%, 0.8%, and 1.4%. During these drift ratio levels, photographs of each specimen were taken at the initial push, the initial pull, and at the end of the displacement cycle. At the end of the displacement cycle grouping, the cripple wall is returned to zero lateral force, and at this point its residual state is defined. Descriptions and images are provided for the 1.4% drift ratio level.

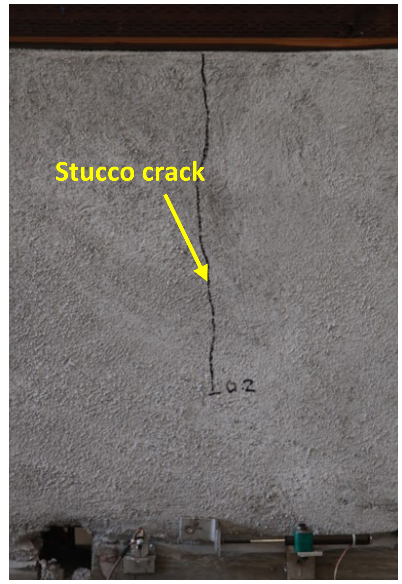
4.2.1 Up to and Including 1.4% Drift Ratio Level for Existing Cripple Walls

Two-Foot-Tall Specimens

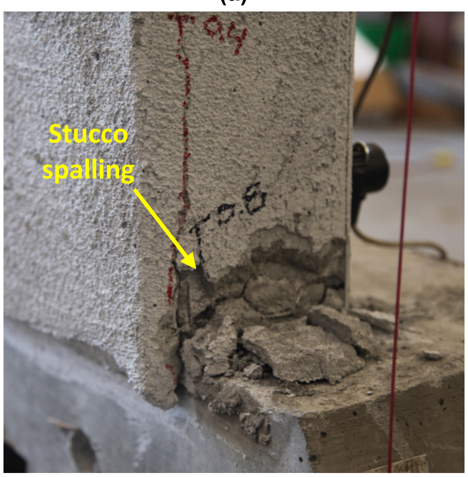
The photographs in Figure 4.1 show the state of the wet finished retrofitted 2-ft-tall cripple walls at ± 1.4% drift ratio, while photographs in Figure 4.2 show the same for dry finished existing 2-ft-tall specimens. It is noted that these photographs were taken while the specimen was held at the prescribed drift amplitude; positive and negative signs are included in the captions to differentiate between push and pull directions of loading. The specimen that each photograph is taken from is included in the caption. A comparison of all wet finished cripple walls indicates that by 1.4% drift, cracking in the stucco had concentrated at the bottom of both corners of the cripple wall in its end wall regions; see Figure 4.1(a). This cracking concentration was due to the bearing of the stucco on the foundation at the ends. In addition, due to the bearing of the stucco on the foundation, spalling of the stucco occurred at the base of the corners, as shown in Figure 4.1(c). In many cases, vertical cracks had propagated on the exterior face of the stucco; see Figure 4.1(b). In general, vertical cracks along the face of the wet finished specimen were minimal. Small displacements of the finish materials relative to the foundation occurred, which was due to both the sill plate displacing relative to the foundation as well as the stucco displacing relative to the foundation. These displacements were typically between 1/8 in. and 1/4 in. for all wet finished specimens; see Figure 4.1(f). At the top of the cripple walls, no displacement of the stucco and finish materials relative to the framing occurred; see Figure 4.1(e).

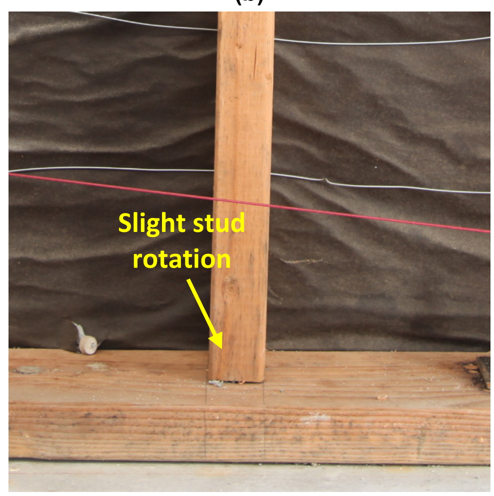
For the dry finished specimens at 1.4% drift ratio, the cripple walls containing horizontal siding had little to no observable damage; see Figure 4.2(a)-(d). Common observations included wrinkling of the building paper and small rotations of the studs; see Figure 4.2(b) and Figure 4.2(c), respectively. The horizontal siding boards and diagonal sheathing boards had little visible displacement and no visible cracking. For the T1-11 finished cripple walls, observable rotation of the panels [see Figure 4.2(e)] and displacement of the trim boards occurred; see Figure 4.2(f). At the panel overlaps of the T1-11 finished cripple walls, only the overlying panels were fastened to the framing while the underlying panels were sandwiched between the overlying panel and the framing. Therefore, even at small displacement amplitudes, panel rotation was observed. Overall, the extent of visible damage for the dry finished specimens was minor in contrast to that of the wet finished specimens at similar drift levels.





(a) (b)





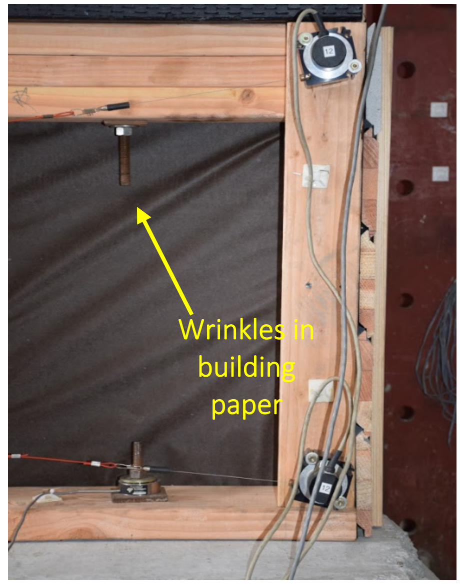
(c) (d)

Figure 4.1 **Damage to the wet finished existing 2-ft-tall specimens at 1.4% drift ratio, positive and negative drift values are noted: (a) south exterior end of Specimen A-17 at -1.4% drift ratio; (b) middle exterior of Specimen A-17 at -1.4% drift ratio; (c) bottom of north-end exterior corner of Specimen A-22 at -1.4% drift ratio; (d) bottom of middle interior of Specimen A-22 at -1.4% drift ratio; (e) top of middle exterior of Specimen A-15 at +1.4% drift ratio; and (f) bottom of middle exterior of Specimen A-15 at +1.4% drift ratio.**

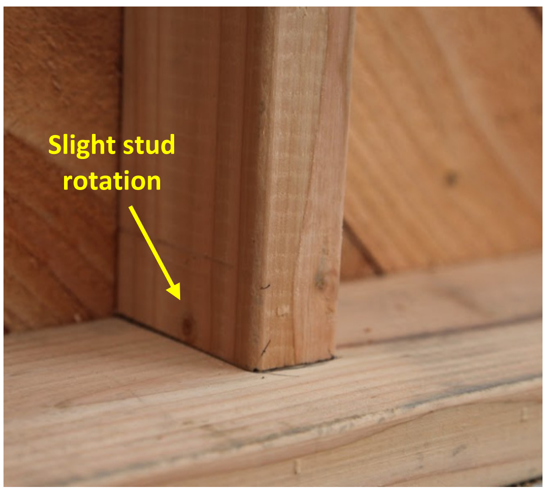
(e) (f)

Figure 4.1 (continued).

(a)



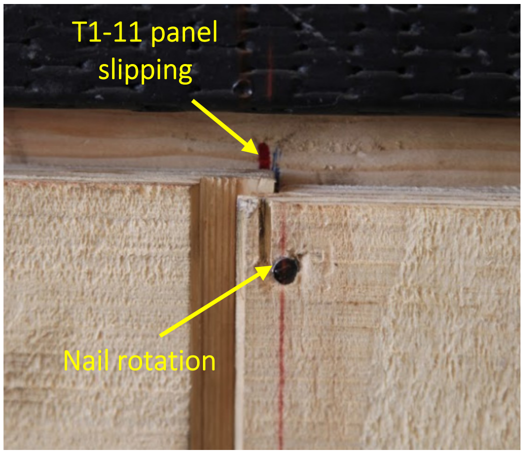
(b)



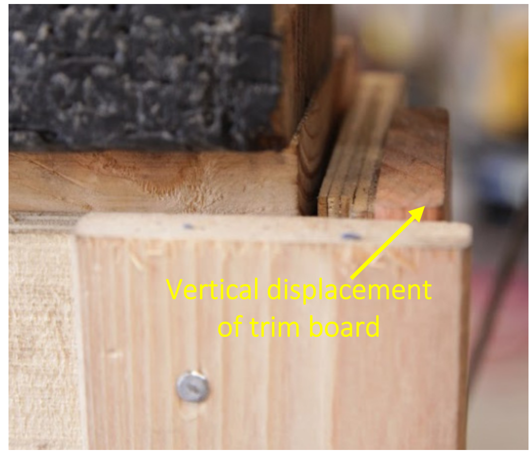
(c)

(d)

Figure 4.2 **Damage to the dry finished existing 2-ft-tall specimens at 1.4% drift ratio, positive and negative drift values are noted: (a) middle exterior of Specimen A-7 at -1.4% drift ratio; (b) south end interior of Specimen A-7 at -1.4% drift ratio; (c) bottom of middle interior of Specimen A-9 at +1.4% drift ratio; (d) south-end of interior of Specimen A-9 at +1.4% drift ratio; (e) top of middle exterior of Specimen A-11 at +1.4% drift ratio; and (f) top of north exterior corner of Specimen A-9 at +1.4% drift ratio.**



(e)



(f)

Figure 4.2 (continued).

Six-Foot-Tall Specimens

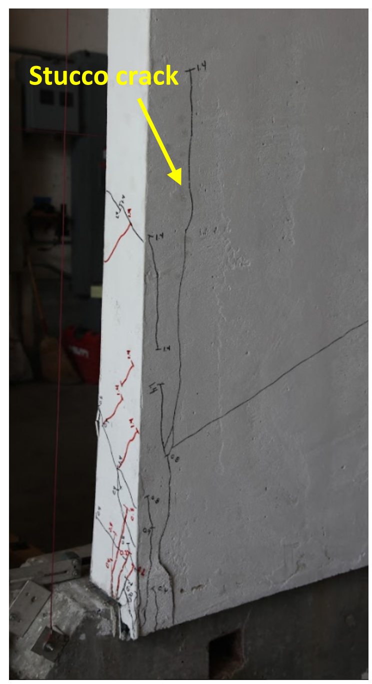
The photographs in Figure 4.3 show the state of the wet finished existing 6-ft-tall cripple walls at ± 1.4% drift ratio, and photographs in Figure show the dry finished existing 6-ft-tall specimens at the same drift ratio. Only one wet finished existing 6-ft-tall cripple wall with stucco over framing was tested (Specimen A-25). There was much more extensive damage to the wet finished retrofitted 6-ft-tall specimen compared to the wet finished existing 2-ft-tall specimens. This was primarily due to the imposed displacement on the 6-ft-tall wall being three times as much compared to the 2-ft-tall walls.

In Figure 4.3(a), several cracks had propagated along the face of the stucco. There was a heavy concentration of vertical cracks at both ends of the stucco face, which propagated from the bottom and extended over half of the height of the specimen: see Figure 4.3(b) and (c). These cracks were a result of the stucco detaching from the framing at the sill plate and bottom of the studs. In addition, diagonal cracks formed at both ends of the cripple wall that extended to the middle of the specimen, which was not observed with the 2-ft-tall specimens. As with the 2-ft-tall specimens, a dense concentration of cracking and some spalling of the stucco at the bottom of the corners on both sides of the specimen was visible, which was due to the bearing of the stucco on the foundation at these locations; see Figure 4.3(d). Along the interior, the studs had not only rotated but displaced as much as 1/4 in.; see Figure 4.3(e). It should be noted that Specimen A-23 reached strength at 1.4% drift ratio.

Two dry finished existing 6-ft-tall specimens were tested; one was finished with horizontal siding over framing (Specimen A-13), and the other was finished with T1-11 wood structural panels (Specimen A-23). As with the horizontal siding finished 2-ft-tall specimen, there was little observable damage; see Figure 4.4(d). Small displacements of the siding boards relative to each other occurred [see Figure 4.4(c)] as well as small rotations of the studs; see Figure 4.4(a). The displacement and rotation of the studs was much less pronounced for the horizontal siding finished specimen compared to the wet finished specimen, which was primarily due to the decreased load being carried by the horizontal siding finished specimen. The damage characteristics of the T1-11 finished cripple wall were similar regardless of cripple wall height, but they were more pronounced with the taller specimen due to the increased imposed displacement. Most notably was the increased rotation of the T1-11 panels and rotation of the fasteners at the top and bottom of the specimen; see Figure 4.4(b) and (f). Uplift of the corner studs and the finish at the corners occurred at the ends of the T1-11 finished specimen; see Figure 4.4(e). The amount of uplift observed for the T1-11 finished specimen corner studs was similar to that of the stucco finished specimens, around 1/4 in.; see Figure 4.4(e).

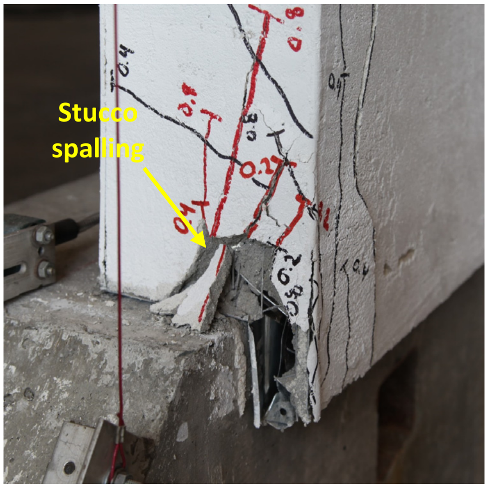
(a)

(b)

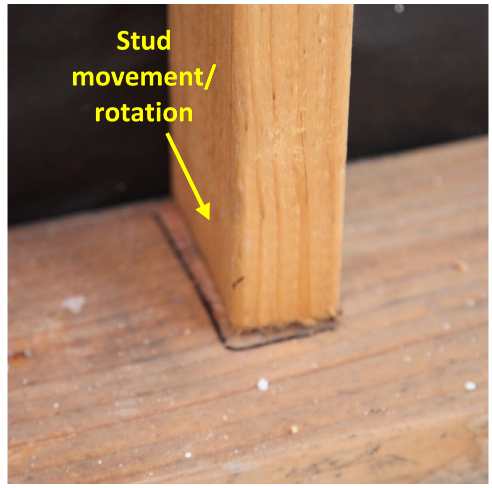


(c)

Figure 4.3 **Damage to the wet finished existing 6-ft-tall specimens at 1.4% drift ratio, positive and negative drift values are noted: (a) exterior elevation of Specimen A-25 at -1.4% drift ratio; (b) north-end exterior corner of Specimen A-25 at -1.4% drift ratio; (c) south-end exterior corner of Specimen A-25 at -1.4% drift ratio; (d) bottom of south-end exterior corner of Specimen A-25 at -1.4% drift ratio; and (e) bottom of middle interior of Specimen A-25 at -1.4% drift ratio.**

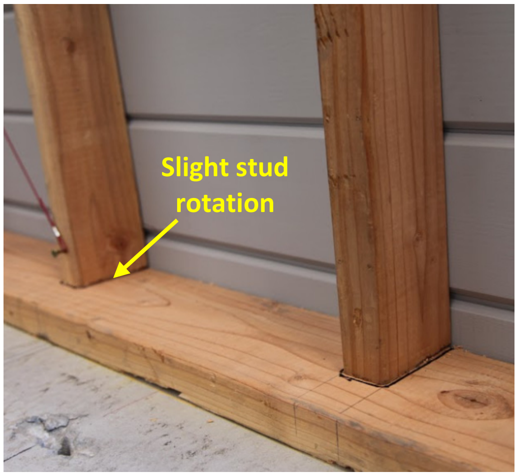


(d)

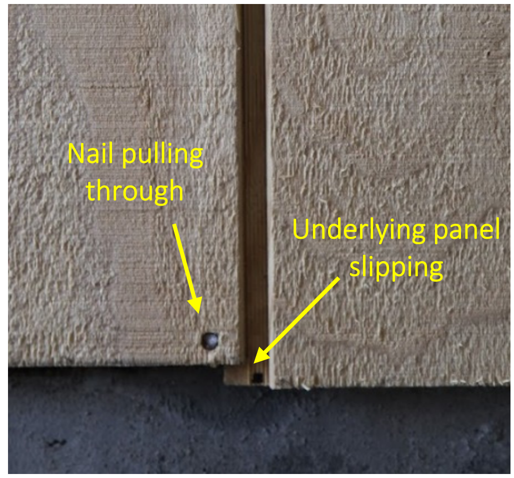


(e)

Figure 4.3 (continued).



(a)

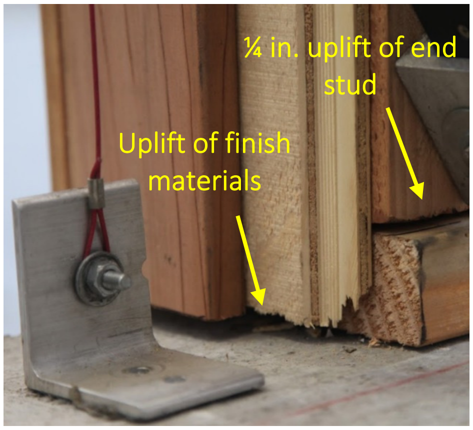


(b)

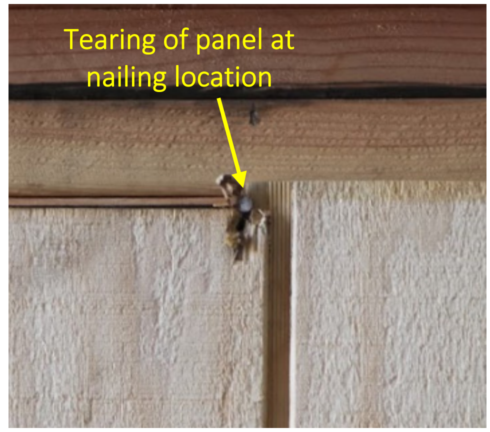
(c)

(d)

Figure 4.4 **Damage to the dry finished existing 6-ft-tall specimens at 1.4% drift ratio, positive and negative drift values are noted: (a) bottom middle interior of Specimen A-13 at +1.4% drift ratio; (b) bottom middle exterior of Specimen A-23 (south and middle panels) at -1.4% drift ratio; (c) middle exterior of Specimen A-13 at +1.4% drift ratio; (d) north-end exterior of Specimen A-13 at +1.4% drift ratio; (e) bottom of south-end interior of Specimen A-23 corner view at +1.4% drift ratio; and (f) top middle exterior of Specimen A-23 (south and middle panels) at +1.4% drift ratio.**



(e)



(f)

Figure 4.4 (continued).

4.2.2 Up to and Including 1.4% Drift Ratio Level for Retrofitted Cripple Walls

Two-Foot-Tall Specimens

The photographs in Figure 4.5 show the state of wet finished retrofitted 2-ft-tall cripple walls at ±1.4% drift ratio, and Figure 4.6 shows the dry finished retrofitted 2-ft-tall specimens at the same drift ratio. A comparison of these photographs indicates that the damage characteristics of the retrofitted components of cripple walls were similar for both wet and dry specimens (i.e., the plywood panelling and its nailing). The damage at 1.4% drift can be characterized by small rotations and uplift of the plywood panels and insipient nail withdrawal/pull through; see Figure 4.5(a) and (b). The cracking patterns in the stucco along the face of the retrofitted wet specimens were more pronounced compared to the existing wet specimens; see Figure 4.5(c). The concentration of cracking at the corners due to the bearing of the stucco on the foundation was similar [see Figure 4.5(d)], but in general there was no spalling of the stucco at this displacement amplitude that was observed with the existing specimens. As with the existing wet finish specimens, displacements of the finish materials relative to the foundation occurred, which was due to both the sill plate and the stucco displacing relative to the foundation. These displacements were typically around 1/4 in. for all wet finished specimens. which was similar to that experienced by the existing specimens; see Figure 4.5(f). Unlike the existing specimens, there was around 1/8-in. displacement of the stucco and finish materials at the top of the cripple walls relative to the framing; see Figure 4.5(e).

For the dry finished 2-ft-tall specimens with horizontal siding, there was no visible damage to the exterior of the specimens; see Figure 4.6(c). This was the same as with the existing specimens. The retrofitted components displayed similar damage characteristics compared to the wet specimens, namely, small rotations of the plywood panels as well as insipient nail withdrawal/pull through; see Figure 4.6(a) and (b). The T1-11 finished cripple walls experienced similar amounts of rotations of T1-11 panels as with the plywood panels used in all other retrofits. The rotations were considerably less than the existing T1-11 finished specimens due to the decreased edge nail spacing and an extra row of nails being added to the underlying panels at the overlaps; see Figure 4.6(e) and (f). Overall, at this displacement amplitude, there was little damage experienced by the finish materials, but more significant damage occurred to the retrofitted components.

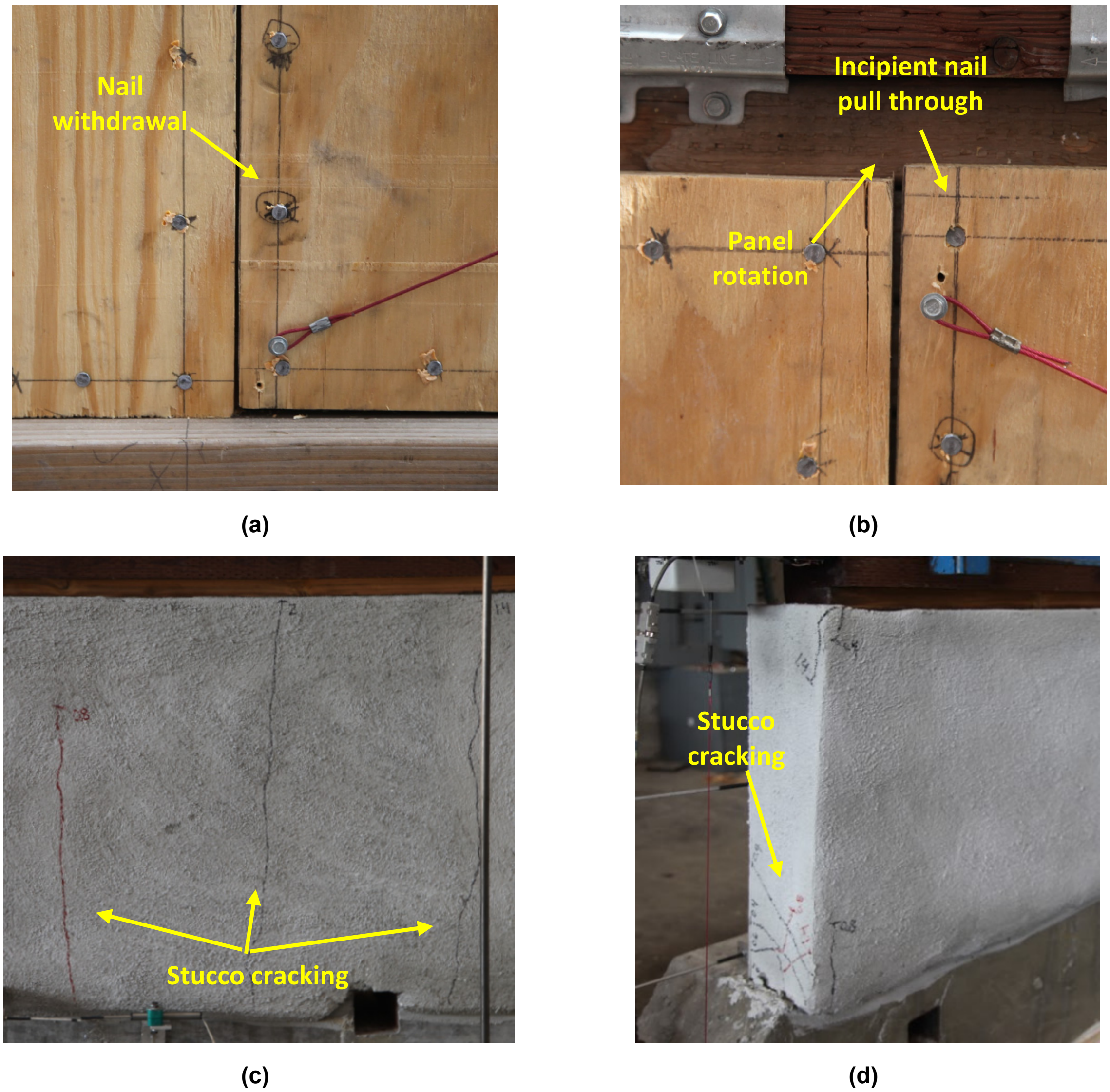
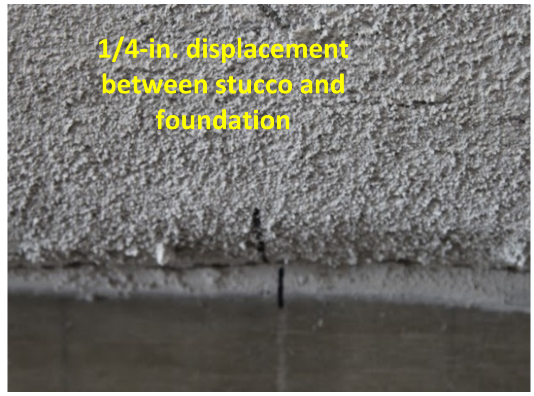


Figure 4.5 **Damage to the wet finished retrofitted 2-ft-tall specimens at 1.4% drift ratio, positive and negative drift values are noted: (a) bottom interior (north and middle panels) of Specimen A-18 at -1.4% drift ratio; (b) top interior (north and middle panels) of Specimen A-18 at -1.4% drift ratio; (c) middle exterior of Specimen A-18 at -1.4% drift ratio; (d) south-end exterior corner of Specimen A-19 at -1.4% drift ratio; (e) top of south-end exterior of Specimen A-19 at -1.4% drift ratio; and (f) bottom of south-end exterior of Specimen A-19 at -1.4% drift ratio.**

(e)



(f)

Figure 4.5 (continued).

(a) (b) (c) (d) (e) (f)

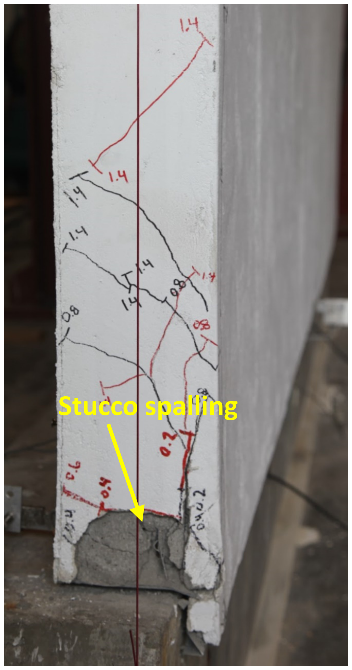
Figure 4.6 Damage to the dry finished retrofitted 2-ft-tall specimens at 1.4% drift ratio, positive and negative drift values are noted: (a) bottom of north interior corner of Specimen A-8 at -1.4% drift ratio; (b) bottom interior (middle and south panels) of Specimen A-8 at -1.4% drift ratio; (c) middle exterior of Specimen A-10 at -1.4% drift ratio; (d) bottom of north-end interior of Specimen A-10 at -1.4% drift ratio; (e) top middle interior of Specimen A-12 (north and middle panels) at +1.4% drift ratio; and (f) top middle interior of Specimen A-12 (south and middle panels) at +1.4% drift ratio.

Six-Foot-Tall Specimens

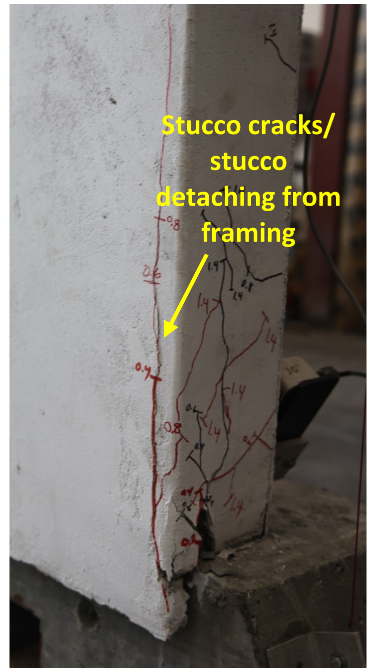
The photographs in Figure show the state of the wet finished retrofitted 6-ft-tall cripple walls at ±1.4% drift ratio, and photographs in Figure show the same for dry finished retrofitted 6-ft-tall specimens. As with the wet finished existing 6-ft-tall specimens, only one 6-ft-tall cripple wall was tested (Specimen A-26). At both corners, vertical cracks had propagated at the base due to the bearing of the stucco on the foundation. This also caused some of the stucco to spall off at these locations; see Figure (a) and (b). The same diagonal cracking pattern at the corners occurred as with the existing specimen. In Figure (b), a vertical crack had begun to open, indicating that the stucco had partially detached from the furring nails at the sill plate and the bottom of the studs. It was evident that the stucco had partially detached due to the out-of-plane displacement of the bottom of the stucco, which is shown by the gap forming between the face of the foundation and the stucco; see Figure 4.7(a). On the interior, the panels had begun to rotate; see Figure 4.7(c)–(e). The fasteners had rotated in many locations, especially at the base of the cripple wall; see Figure 4.7(d). At the top of the cripple wall, fasteners tended to withdraw from the framing; see Figure 4.7(e). Unlike the retrofitted 2-ft-tall specimens, a more definitive pattern was observed as to whether the nails would withdraw from the framing or pull through the plywood. At the top, the nails would withdraw, and at the bottom the nails would pull through. At the bottom corners, the plywood was bearing on the sill plate and end studs, showing incipient crushing of the panels; see Figure 4.7(f).

As with all of other cripple walls with horizontal siding, there was no observable damage to the siding boards at 1.4% drift ratio. Most notable were the small displacements of the siding boards relative to each other, which was around the same magnitude as the existing specimen; see Figure 4.8(c). The damage characteristics of the retrofit materials were similar for both the wet and dry finished specimens, namely, small rotation of the plywood panels and insipient nail withdrawal/pull through of the fasteners attaching the plywood to the framing; see Figure 4.8(a) and 4.8(b). Splitting of blocking was observed for the horizontal siding finished specimen, which was a common occurrence for all retrofitted specimens, regardless of height or finish materials; see Figure 4.8(b).

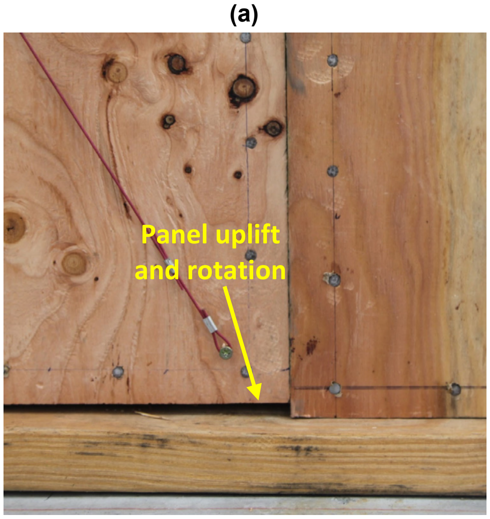
For the retrofitted 6-ft-tall cripple wall finished with T1-11 wood structural panels, there was observable bending of the sill plate in the middle of the span [Figure 4.8(d)] as well as around 1/4-in. uplift of the studs; see Figure 4.8(e). The uplift was more pronounced for the T1-11 finished specimen than all other retrofitted 6-ft-tall specimens because it was the only specimen that was not retrofitted with hold-downs at both ends of the wall. Along the exterior face, the rotation of the T1-11 panels was more significant compared to the T1-11 finished retrofitted 2-ft-tall specimen but significantly less compared to the existing 6-ft-tall specimen; see Figure 4.8(f). This was due to the increased imposed displacement on the 6-ft-tall specimens (which increased the panel rotation) and the denser nailing arrangement of the retrofit (which decreased the panel rotation).



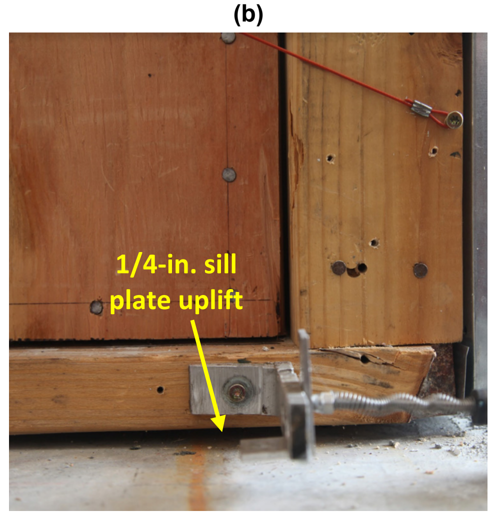
(a)



(b)

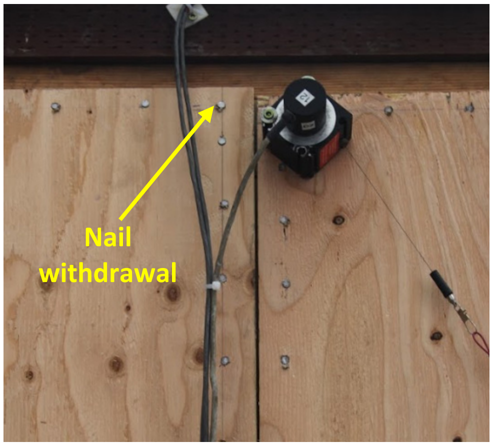


(c)

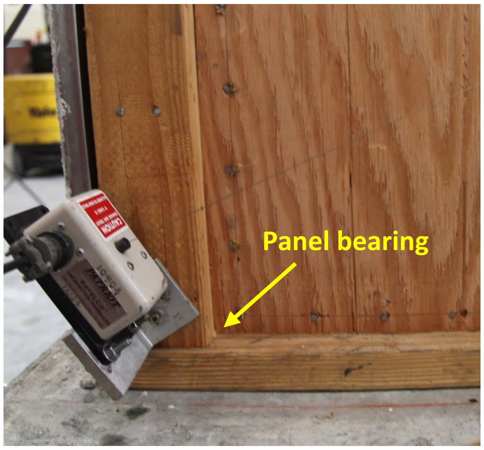


(d)

Figure 4.7 **Damage to the wet finished retrofitted 6-ft-tall specimens at 1.4% drift ratio, positive and negative drift values are noted: (a) bottom of south-end exterior corner of Specimen A-26 at -1.4% drift ratio; (b) bottom of north-end exterior corner of Specimen A-26 at -1.4% drift ratio; (c) bottom interior of Specimen A-26 (south and middle panels) at -1.4% drift ratio; (d) bottom of south-end interior of Specimen A-26 at -1.4% drift ratio; (e) top interior of Specimen A-26 (north and middle panels); and (f) bottom of north-end corner of Specimen A-26 at -1.4% drift rate.**

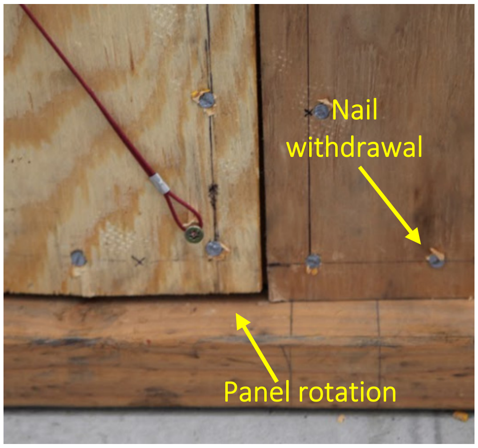


(e)

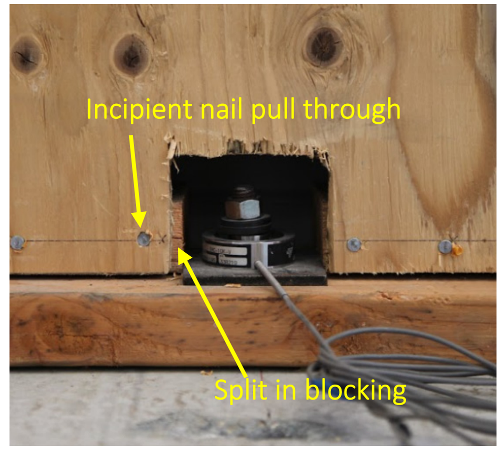


(f)

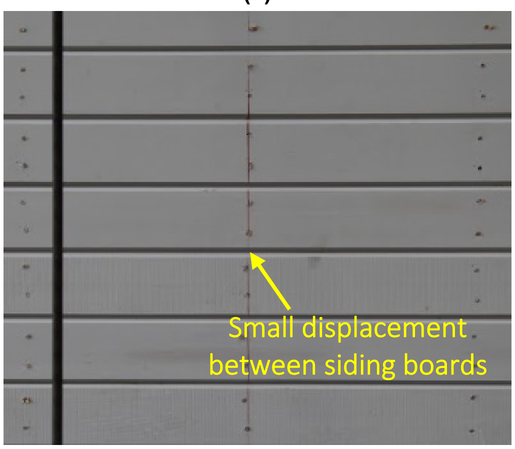
Figure 4.7 (continued).



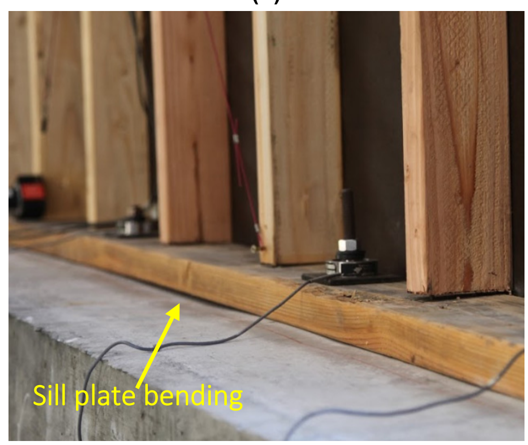
(a)



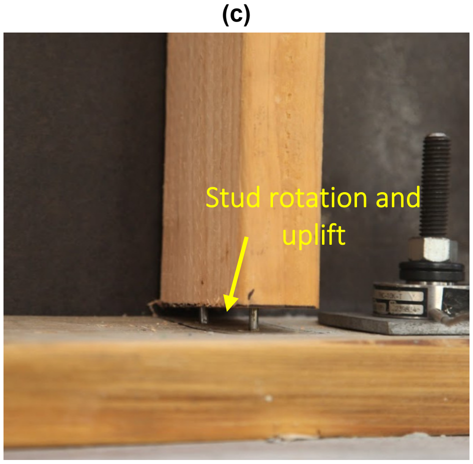
(b)



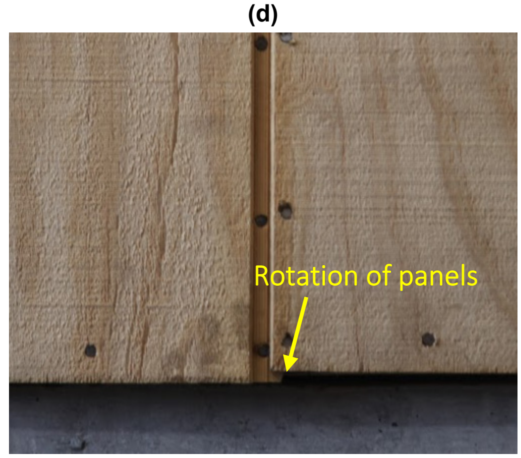
(c)



(d)



(e)



(f)

Figure 4.8 **Damage to the dry finished retrofitted 6-ft-tall specimens at 1.4% drift ratio, positive and negative drift values are noted: (a) bottom middle interior Specimen A-14 (north and middle panels) at -1.4% drift ratio; (b) bottom of north-end interior of Specimen A-14 at -1.4% drift ratio; (c) middle exterior of Specimen A-14 at -1.4% drift ratio; (d) bottom of interior of Specimen A-24 at 1.4% drift ratio; (e) bottom of interior of Specimen A-24 at -1.4% drift ratio; and (f) bottom of middle exterior Specimen A-24 (south and middle panels) at -1.4% drift ratio.**

4.3 DAMAGE CHARACTERISTICS AT LATERAL STRENGTH

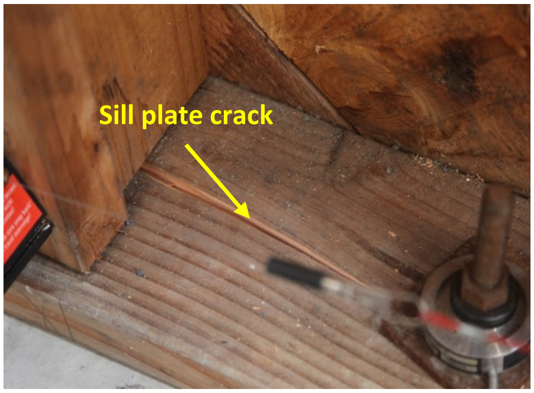
A key damage state consistently discussed in prior analysis of individual specimens is when the lateral strength of the cripple wall is attained. To this end, the patterns of damage features of the various finish specimen types presented in this section. Examination of the damage states at this level provides insight into the failure mechanism of a cripple wall. All lateral strengths for the existing dry finished specimens occurred across a wide range of drift levels, namely between 2.0-–12.0% global drift ratio and 2.0–12.0% relative drift ratio. For the existing wet finished specimens, lateral strength was achieved between 1.4–5.0% global drift ratio and 1.0–2.5% relative drift ratio. The range for the dry finished retrofitted specimens were 2.0–8.0% global drift ratio and 2.0–6.4% relative drift ratio, and for the wet finished retrofitted specimens, 2.0–8.0% global drift ratio and 2.1–5.3% relative drift ratio.

4.3.1 Lateral Strength of Existing Cripple Walls

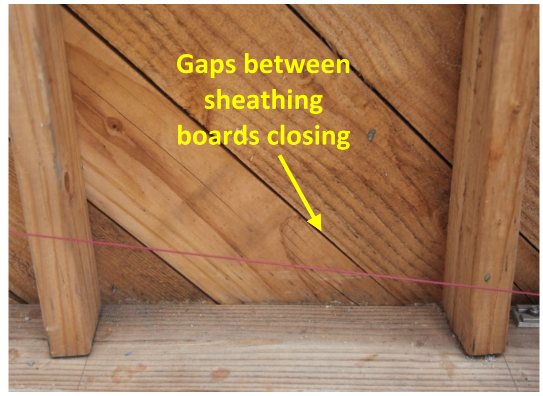
Two-Foot-Tall Specimens

Figure 4.9 shows observable damage at lateral strength for the wet finished existing 2-ft-tall cripple walls, and Figure 4.10 shows the observable damage for the dry finished existing 2-ft-tall cripple walls. The drift ratio values and specimen names for each of the photographs are given in the captions. For all wet finished specimens, the stucco detached from the sill plate and the bottom of the studs at strength, leading to a loss in strength in subsequent drift cycles; see Figure 4.9(d) and (e). Cracking on the face of the stucco and end walls propagated up the wall height for all wet specimens as the stucco detached from the furring nails progressed; see Figure 4.9(c). The cracks at the ends of the specimens propagated along the entire height of the cripple wall. Typically, the cracks were vertical at the base where the stucco was bearing on the foundation and diagonal along the rest of the height due to the imposed displacement. For the stucco over diagonal sheathing specimen, cross-grain sill plate cracks formed at both ends of the wall; see Figure 4.9(a). The cracking of the sill plate occurred due to the uplift of the diagonal sheathing boards when the cripple wall was being loaded in the push direction. In the pull loading direction, the gaps between the diagonal sheathing boards had nearly all closed at strength for both specimens; see Figure 4.9(b). At the bottom of the specimens, increased displacement of the finish materials relative to the foundation occurred, which was due to both the displacement of the sill plate relative to the foundation and the finish materials relative to the sill plate. This displacement was between 3/8 and 1/2 in. for all wet finished existing 2-ft-tall specimens.

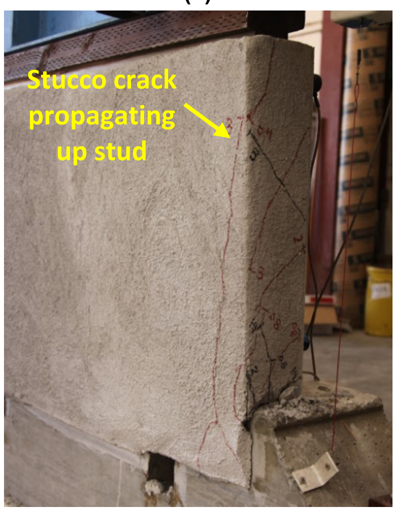
For the dry specimens at strength, there was little visible damage to the horizontal siding finished specimens. The most notable observation was the development of a ~1/4-in. displacement between the siding boards; see Figure 4.10(e). In addition, tearing of the building paper at the location of the studs occurred along the interior of the specimen; see Figure 4.10(f). The damage characteristics along the interior for the horizontal siding over diagonal sheathing specimen was similar to that which occurred for the stucco over diagonal sheathing specimen. Cross-grain sill plate cracks developed at both ends of the wall [see Figure 4.10(a)], and the gaps between the sheathing boards closed; see Figure 4.10(b). Compared to the wet finished specimen, smaller gaps between the sheathing boards of the dry finished specimen occurred, which was a result of the dry finished specimen reaching strength at a later displacement amplitude than the wet finished specimen. For the T1-11 finished cripple walls, the panel had rotated significantly [see Figure 4.10(c)], and some of the nails had torn through the edges of the panels; see Figure 4.10(d).



(a)

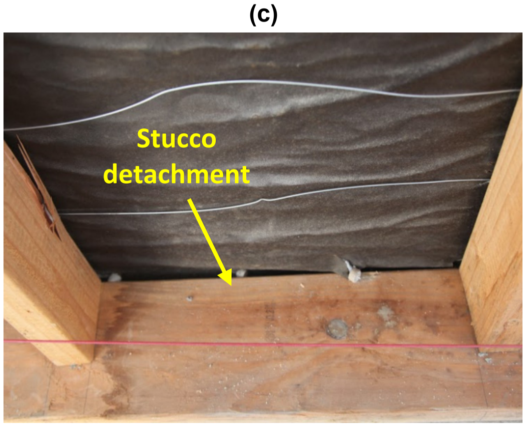


(b)

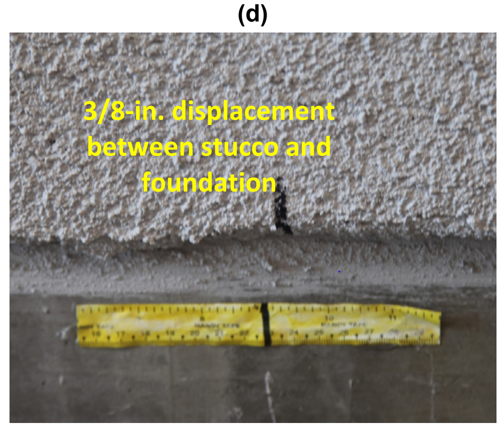


(c)

(d)



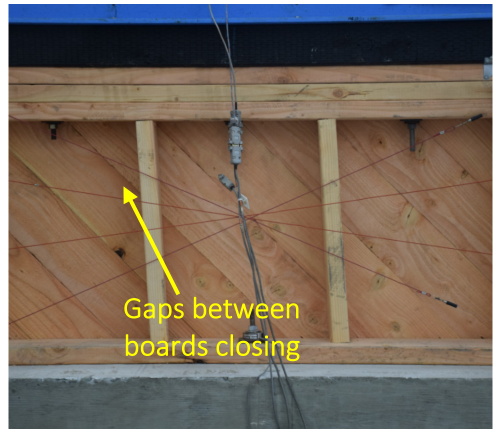
(e)



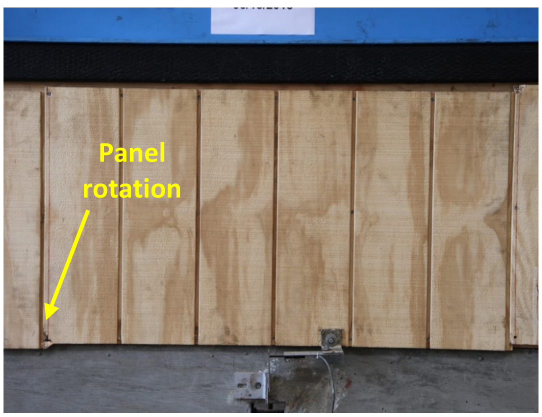
(f)

Figure 4.9 **Damage to the wet finished existing 2-ft-tall specimens at lateral strength. Drift values are noted: (a) bottom of north-end interior of Specimen A-15 at +5% drift ratio; (b) bottom of middle interior of Specimen A-15 at -4% drift ratio; (c) north-end exterior corner of Specimen A-17 at -3% drift ratio; (d) bottom of south-end corner of Specimen A-17 at -3% drift ratio; (e) bottom middle interior of Specimen A-22 at -2% drift ratio; and (f) bottom of north-end exterior of Specimen A-22 at -2% drift ratio.**

(a)



(b)

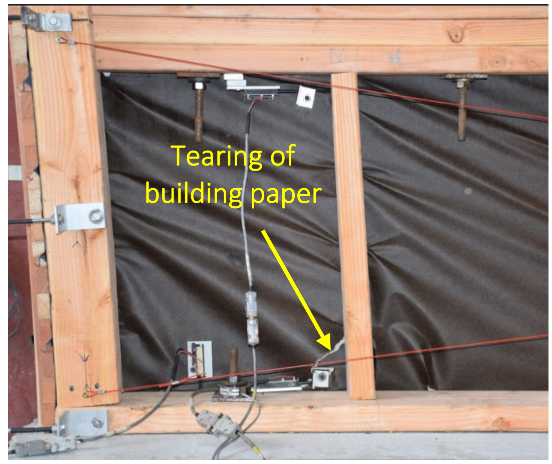


(c)

(d)

Figure 4.10 **Damage to the dry finished existing 2-ft-tall specimens at lateral strength. Drift values are noted: (a) bottom of south-end interior of Specimen A-9 at -10% drift ratio; (b) middle interior of Specimen A-9 at -10% drift ratio; (c) middle exterior of Specimen A-11 at -5% drift ratio; (d) bottom of middle exterior (south and middle panel) of Specimen A-11 at -5% drift ratio; (e) south-end exterior of Specimen A-7 at -4% drift ratio; and (f) north-end interior of Specimen A-7 at -4% drift ratio.**

(e)



(f)

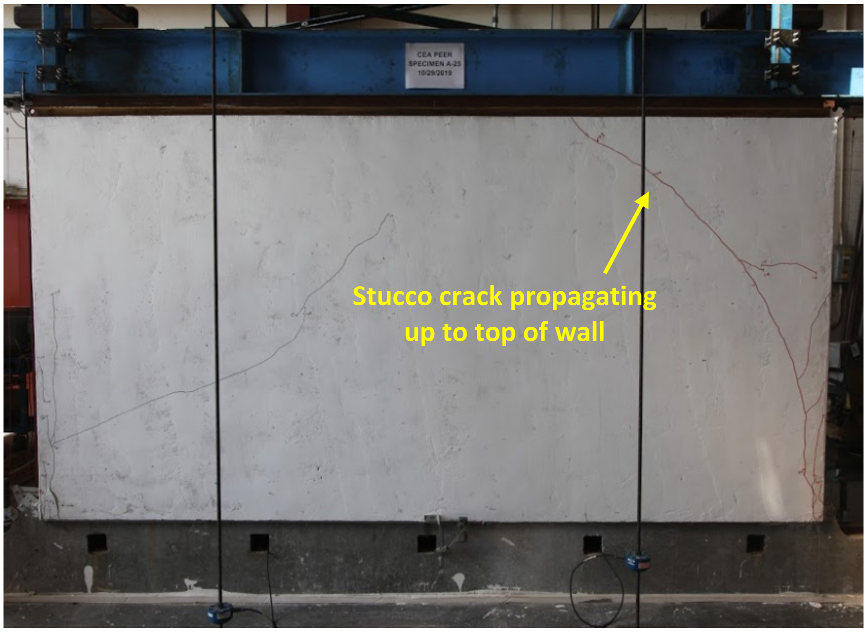
Figure 4.10 (continued).

Six-Foot-Tall Specimens

Figure 4.11 shows that damage at lateral strength for the existing 6-ft-tall wet finished cripple walls, and Figure 4.12 shows the damage at lateral strength for the existing 6-ft-tall dry finished cripple walls. Only one existing 6-ft-tall wet finished specimen with stucco over framing was tested (Specimen A-25). At strength, large diagonal cracks extended across the exterior face of the specimen; see Figure 4.11(a). The crack openings were largest where the vertical cracks had formed at the bottom of the wall and then propagated upward at both ends of the specimen. These crack openings indicated the stucco had detached from the furring nails at the sill plate and bottom of the studs. The detachment of the stucco from the sill plate can be seen from the interior in Figure 4.11(c). Heavy spalling of the stucco occurred at both corners, which was primarily due to the corners bearing on the foundation; see Figure 4.11(d). Visible bending of the studs along the interior of the wall occurred, which had not occurred with any of the 2-ft-tall cripple walls [Figure 4.11(b)].

Lateral strength for the existing 6-ft-tall cripple wall finished with horizontal siding was achieved at -11% and +12% drift ratio, which was by far the largest drift amplitude achieved compared to any of the cripple walls tested. By comparison, the existing 6-ft-tall cripple wall finished with T1-11 achieved strength at -2% and +3% drift ratio. In addition, Specimen A-13 had the lowest peak load of any of the cripple walls tested. There was little damage to both the interior and exterior face of the cripple wall at strength. Figure 4.12(a) shows the north-end corner of the exterior of Specimen A-13. No cracking of the siding boards or trim boards occurred, although. There was around 1/2 in. of displacement between each of the siding boards; see Figure 4.12(c). Significant rotation of the studs along the interior occurred; see Figure 4.12(b). Due to the low strength of the cripple wall, little uplift occurred.

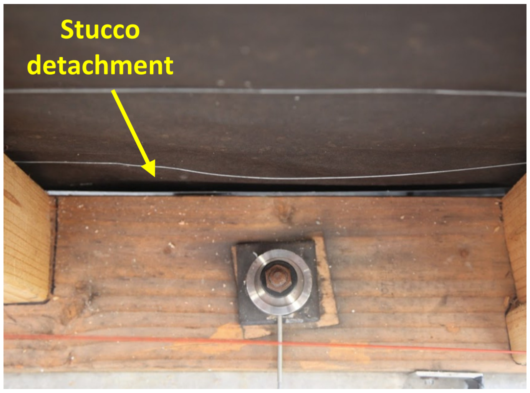
The horizontal siding specimen exhibited the least amount of damage at strength of any of the specimens tested. The T1-11 finished existing 6-ft-tall cripple wall accumulated significant damage. Figure 4.12(d) shows the panels pulling away from the sill plate, with the largest gap formed at the panel overlap where the underlying panel did not have any nails on that edge. The sill plate shows less uplift and rotation than in previous displacement cycles due to the reduced amount of nailing attaching the sill plate to panels, i.e., the nails pulling through the panel at the sill plate. At the corners, the studs uplifted 1/4 in. from the sill plate, which had not experienced any increase compared with the state of the specimen at 1.4% drift ratio; see Figure 4.12(f). This is more uplift compared to that experienced by the horizontal siding finished specimen, and the mechanism is similar that experienced by the stucco finished specimen. Along the overlap joints of the T1-11 panels, the underlying panel displaced relative to the overlying panel due to the confinement of the overlying panel on the underlying panel being primary source of resistance to displacement of the underlying panel. Thus, significant rotations of the panels occurred, and the mechanism was similar to that of the existing 2-ft-tall specimen at strength; see Figure 4.12(e).



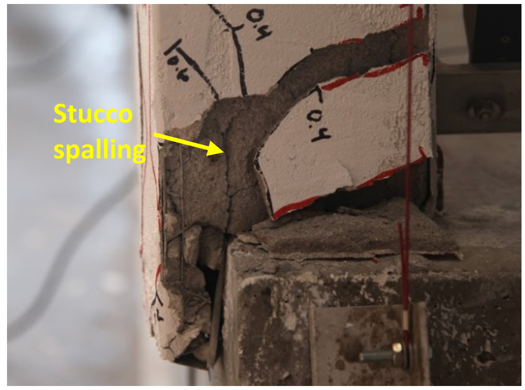
(a)

(b)

Figure 4.11 **Damage to the wet finished existing 6-ft-tall specimens at lateral strength. Drift values are noted: (a) exterior elevation of Specimen A-23 at -1.4% drift ratio; (b) interior elevation of Specimen A-23 at -1.4% drift ratio; (c) bottom of middle interior of Specimen A-25 at -1.4% drift ratio; and (d) bottom of south-end corner of Specimen A-25 at -1.4% drift ratio.**

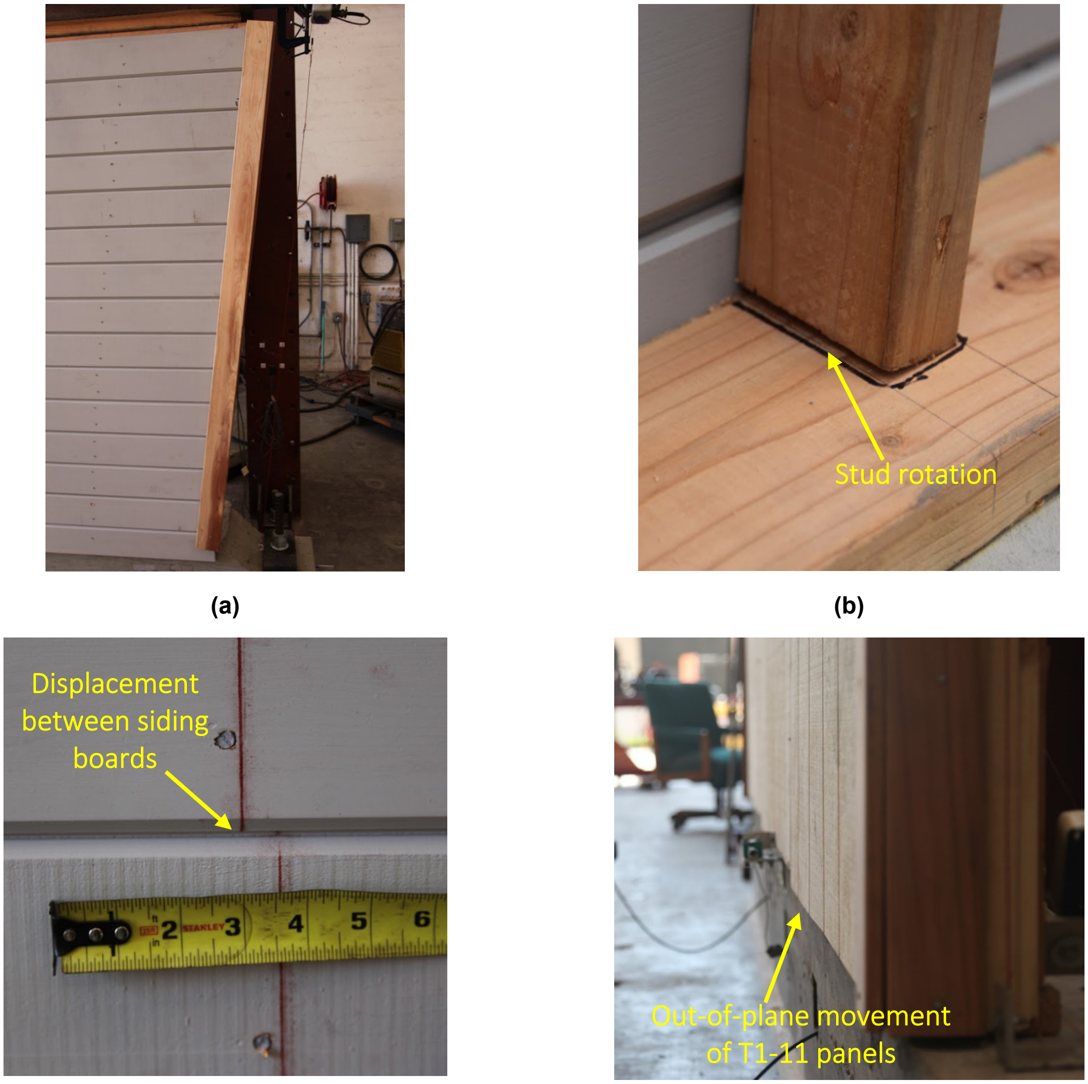


(c)



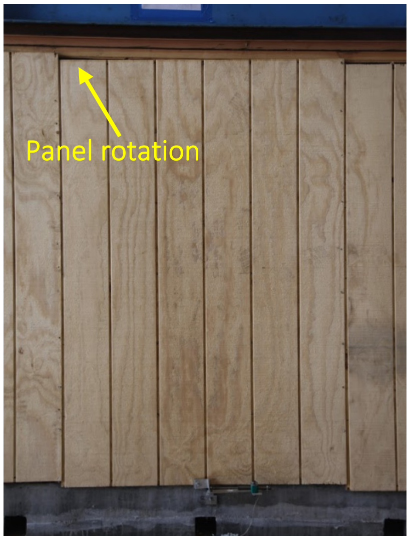
(d)

Figure 4.11 (continued).

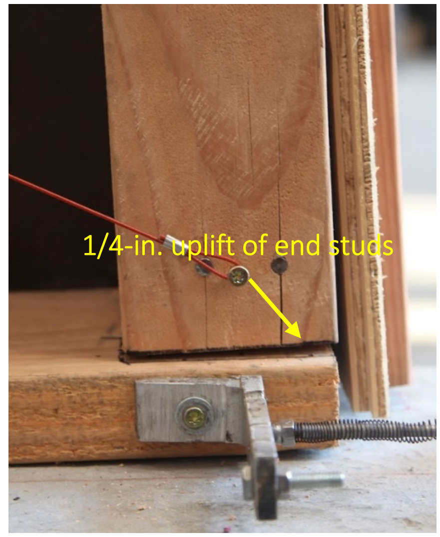


(a) (b) (c) (d)

Figure 4.12 **Damage to the dry finished existing 6-ft-tall specimens at lateral strength. Drift values are noted: (a) north-end exterior of Specimen A-13 at +11% drift ratio; (b) bottom of middle interior of Specimen A-13 at +12% drift ratio; (c) middle exterior of Specimen A-13 at -12% drift ratio; (d) bottom of north-end exterior of Specimen A-23 corner at -2% drift ratio; (e) middle exterior of Specimen A-23 at +3% drift ratio; and (f) bottom of north-end interior of Specimen A-23 at +3% drift.**



(e)



(f)

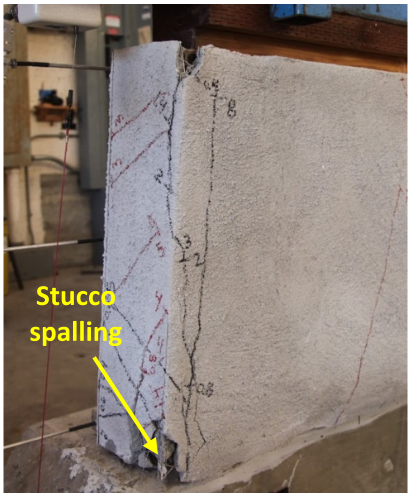
Figure 4.12 (continued).

4.3.2 Lateral Strength of Retrofitted Cripple Walls

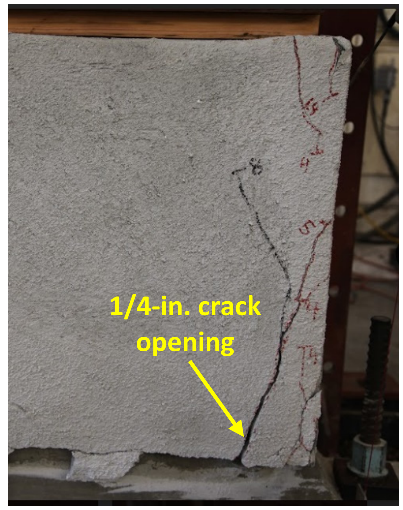
Two-Foot-Tall Specimens

Figure 4.13 shows damage incurred at lateral strength for the wet finished retrofitted 2-ft-tall cripple walls, and Figure 4.14 shows the same for the dry finished retrofitted 2-ft-tall cripple walls. Near the corners of the exterior face of the specimen, vertical cracks propagated up the entire height of the wall; see Figure 4.13(a). In addition, the vertical cracks at the bottom of the wall had opened up significantly; see Figure 4.13(b). This response was like that experienced by the retrofitted specimens, indicating that the stucco had detached from the sill plate and bottom of the studs. The observed damage along the interior was manifested by plywood uplift and rotation; see Figure 4.13(c), (d), and (e). Many of the nails fastening the panels to the framing had rotated, and some had torn through the plywood panel; see Figure 4.13(f). In addition, splitting of some of the blocking attaching the plywood to the framing occurred; see Figure 4.13(e). The location of the split blocks was concentrated towards the ends of the specimens for all retrofitted cripple wall tested. The corner studs had uplifted roughly around 1/4 in. at the ends, which was a common occurrence for all retrofitted 2-ft-tall cripple walls.

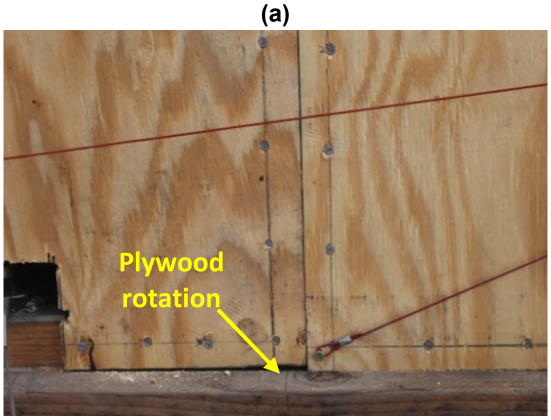
For the retrofitted 2-ft-tall cripple wall with dry exterior finishes containing plywood, the damage characteristic to the retrofitted materials was similar to that of the wet finished 2-ft-tall specimens. There was rotation and uplift of the plywood panels; see Figure 4.14(a), (b), and (e). Many of the nails had rotated heavily, withdrawn from the framing, pulled through the framing, or tore through the edges of the plywood; see Figure 4.14(a) and (b). The horizontal siding over diagonal sheathing finished cripple wall experienced the most significant damage. Several of the anchor bolts were bent; see Figure 4.14(f). Splitting and uplifting of the blocking used to attach the sill plate to the framing was observed in many of the specimens as well; see Figure 4.14(e). The stucco over diagonal sheathing retrofit experienced similar damage. The specimens containing diagonal sheathing experienced the most damage to both the framing and the retrofit materials. This was due to the large loads experienced by these specimens resulting in both fractured anchor bolts and cross-grain sill splits. In addition, the diagonal sheathing specimens had the most uplift of any of the 2-ft-tall cripple walls tested. For the T1-11 finished cripple walls, the T1-11 panels rotated significantly when the specimen reached strength, and many of the nails in the grooves had pulled through the panels, and the nails fastened to the thicker sections of the panels had rotated significantly; see Figure 4.14(c) and Figure 4.14(d). The amount of rotation was less for the T1-11 finished retrofitted 2-ft-tall specimen than the that of the existing specimen due to the denser nail spacing.



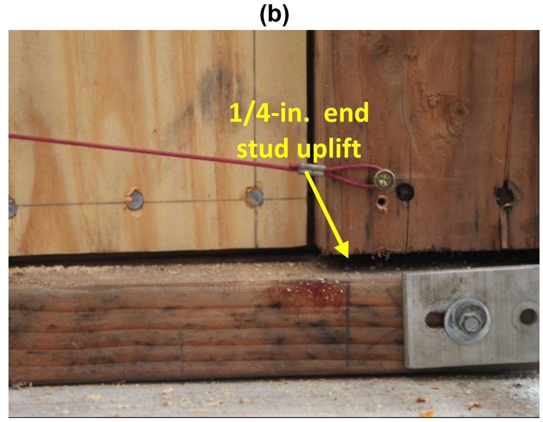
(a)



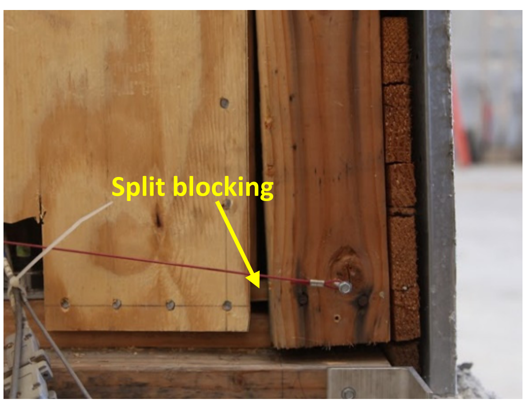
(b)



(c)



(d)



(e)

(f)

Figure 4.13 **Damage to the wet finished retrofitted 2-ft-tall specimens at lateral strength. Drift values are noted: (a) south-end exterior corner of Specimen A-19 at +8% drift ratio; (b) north-end exterior of Specimen A-19 at +8% drift ratio; (c) bottom interior (south and middle panels) of Specimen A-16 at -5% drift ratio; (d) bottom of south-end interior of Specimen A-16 at -5% drift ratio; (e) bottom of south-end interior Specimen A-19 at +8% drift ratio; and (f) bottom of north-end interior Specimen A-19 at +8% drift ratio.**

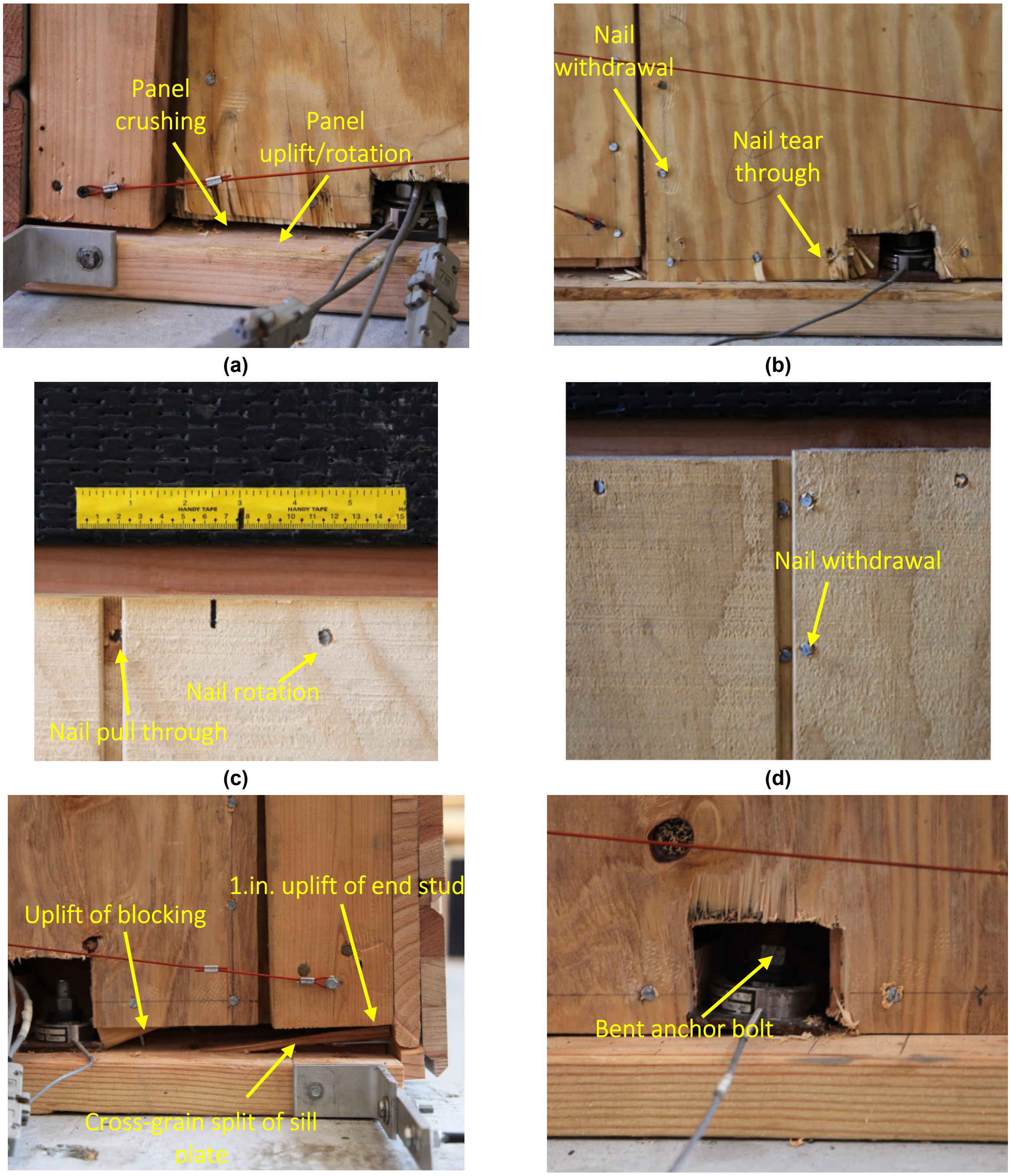


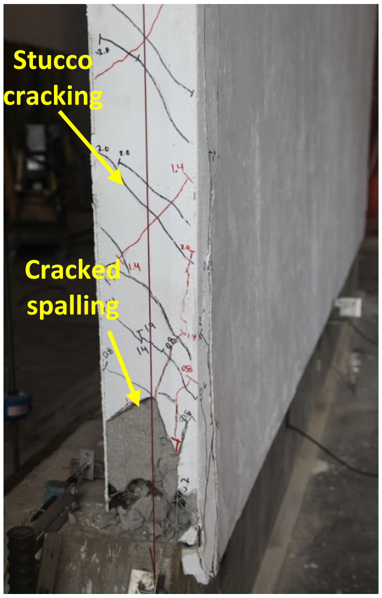
Figure 4.14 **Damage to the dry finished retrofitted 2-ft-tall specimens at lateral strength. Drift values are noted: (a) bottom of north-end interior of Specimen A-8 at +8% drift ratio; (b) bottom of middle interior of Specimen A-8 (north and middle panels) at +8% drift ratio; (c) top of south-end interior of Specimen A-12 at +7% drift ratio; (d) top of middle exterior of Specimen A-12 (north and middle panel) at +7% drift ratio; (e) bottom of south-end interior of Specimen A-10 at -8% drift ratio; and (f) bottom of middle interior of Specimen A-10 at -8% drift ratio.**

Six-Foot-Tall Specimens

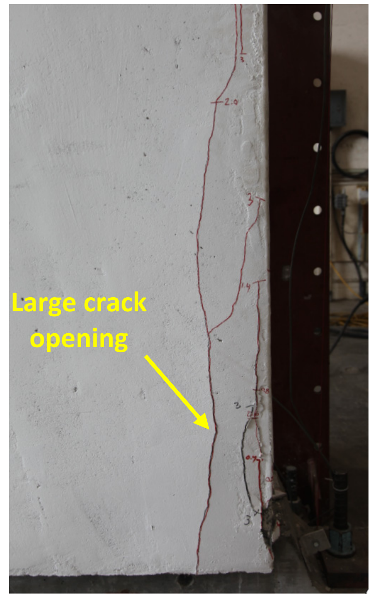
Figure 4.15 shows damage observations at lateral strength for the wet finished retrofitted 6-ft-tall cripple walls, and Figure 4.16 shows the same for the dry finished retrofitted 6-ft-tall cripple walls. As with the existing 6-ft-tall specimen with stucco exterior finish, large cracks had formed in the stucco at the ends of the exterior face, starting from the bottom and propagating upward; see Figure 4.15(b). This indicates that the stucco had detached from the furring nails at the base of the studs. Heavy concentration of cracking formed in the stucco at both corners, much of the stucco had spalled off see Figure 4.15(a) and (d). The stucco had also detached from the framing at the bottom of both corners. Along the interior, the plywood panels were crushed due to bearing on the flat studs, as shown in Figure 4.15(c). Many of the nails had rotated, pulled through the plywood, or withdrawn from the framing; see Figure 4.15(c), (e), and (f). Uplift of both the sill plate and the plywood panels occurred. The sill plate would bend at the ends of the cripple walls; see Figure 4.15(f). Tie-downs were used to inhibit the cripple wall from uplifting, so the visible bending demonstrated how much uplift force was being experienced by the cripple wall.

For the retrofitted 6-ft-tall cripple wall with horizontal siding, the plywood panels detached at many locations, which were typically concentrated towards one side or the top; see Figure 4.16(a). The nails remained fastened to the blocking at the sill plate, which caused the blocking to uplift; see Figure 4.16(b). The nails pulled through the plywood at the top instead of the bottom of the cripple wall because the top plates are more restrained than the blocking attached to the sill plate. Once the plywood panels had lost their attachment at the top, the cripple wall lost capacity. Intrinsic to a taller wall is increased flexure. This is shown by the detachment of the corner studs added for plywood attachment at the top of the cripple wall and not the bottom; see Figure 4.16(c). Not only was there uplift of the blocking, but the sill plate experienced 3/8-in. uplift at lateral strength, which was less than that experienced by the stucco finished specimen.

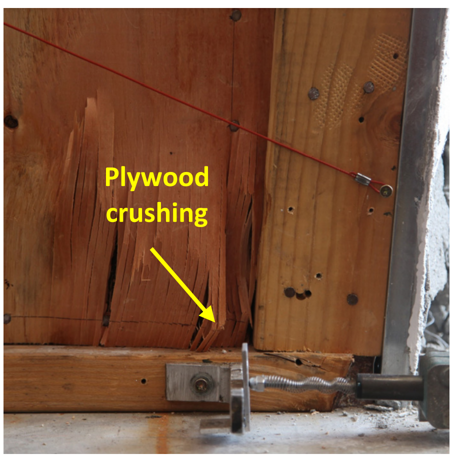
On the exterior face of the cripple wall, cracks formed on the upper siding boards at the corners. The corner trim boards remained uncracked. For the retrofitted 6-ft-tall specimen with T1-11 wood structural panels, extensive uplift of the studs occurred throughout the span as well as at the corner studs; see Figure 4.16(d) and Figure 4.16(e). The increased uplift compared with other retrofitted 6-ft-tall cripple walls was due to the absence of hold-downs at the ends of the specimen. The cross-grain cracks in the sill plate at the ends of the wall continued to increase in size and length; see Figure 4.16(e). The sill plate remained resting on the foundation along the interior face of the wall while it rotated and uplifted on the exterior face of the wall due to the rotation of the T1-11 panels. From the finish face, the nails fastened to the 5/8-in.-thick T1-11 panels were rotated, while the nails at the overlaps of the panels had started to pull through the panels; see Figure 4.16(f). A similar mechanism occurred with the retrofitted 2-ft-tall cripple wall with T1-11 wood structural panels.



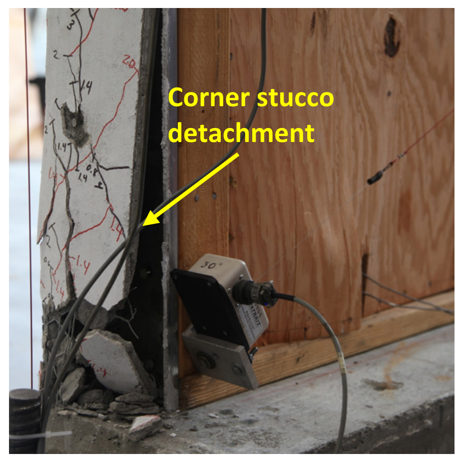
(a)



(b)

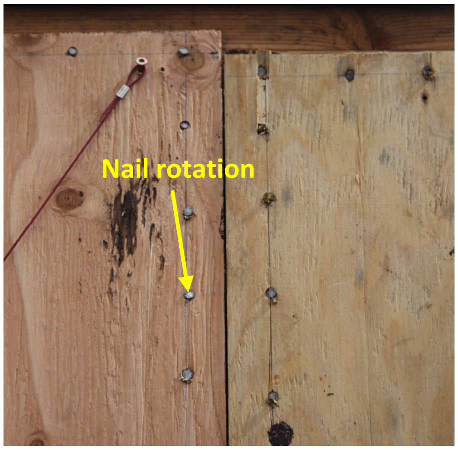


(c)

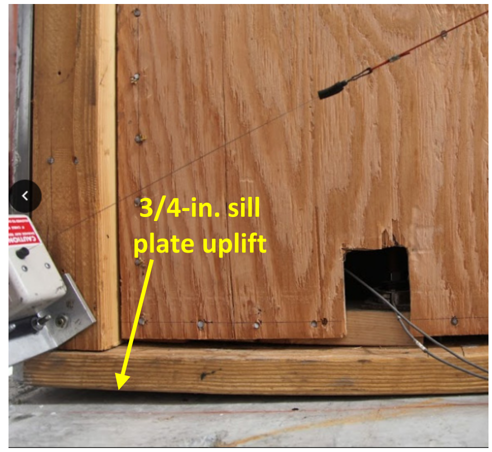


(d)

Figure 4.15 Damage to the wet finished retrofitted 6-ft-tall specimens at lateral strength. Drift values are noted: (a) bottom of south-end exterior corner of Specimen A-26 at -3% drift ratio; (b) bottom of north-end exterior corner of Specimen A-26 at -3% drift ratio; (c) bottom of south-end interior of Specimen A-26 at +3% drift ratio; (d) bottom of north-end interior corner Specimen A-26 at -3% drift ratio; (e) top interior of Specimen A-26 at -3% drift ratio (north and middle panels); and (f) bottom of north-end interior Specimen A-26 at +3% drift ratio.



(e)



(f)

Figure 4.15 (continued).

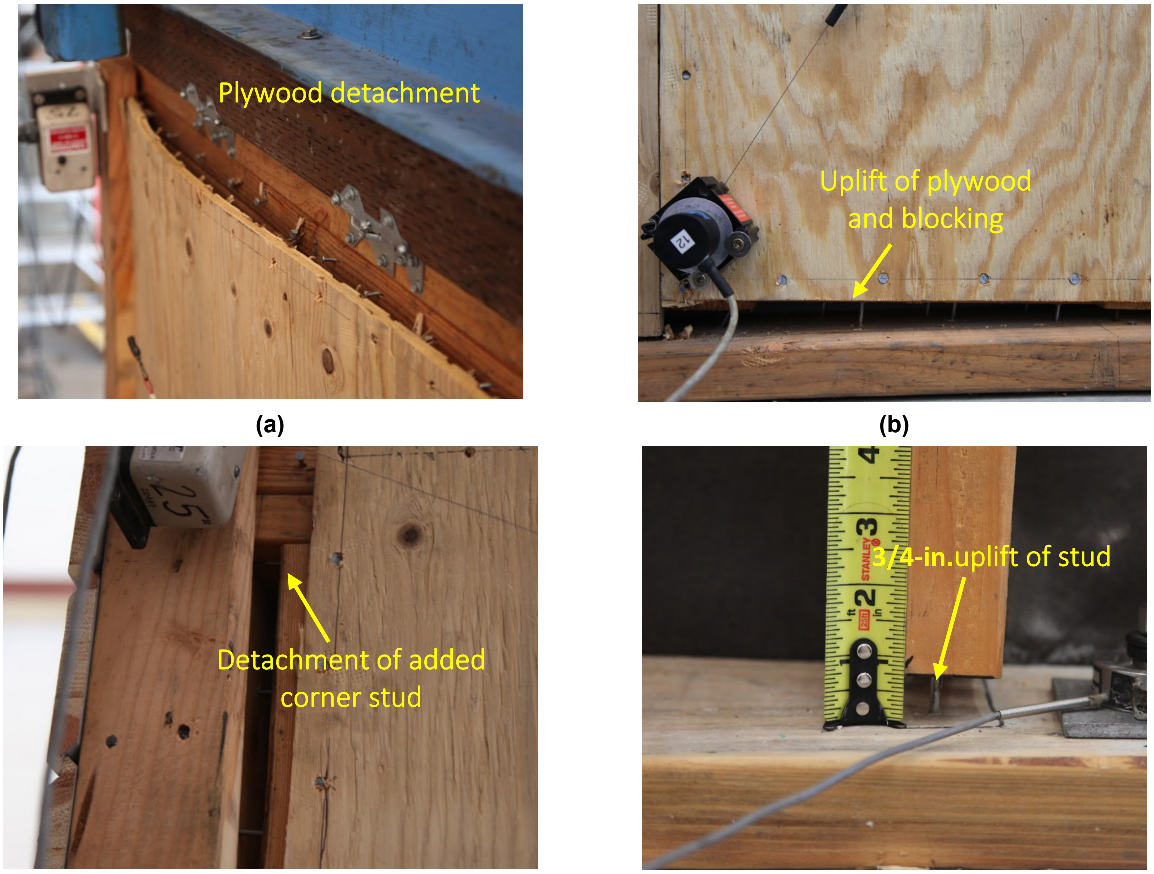
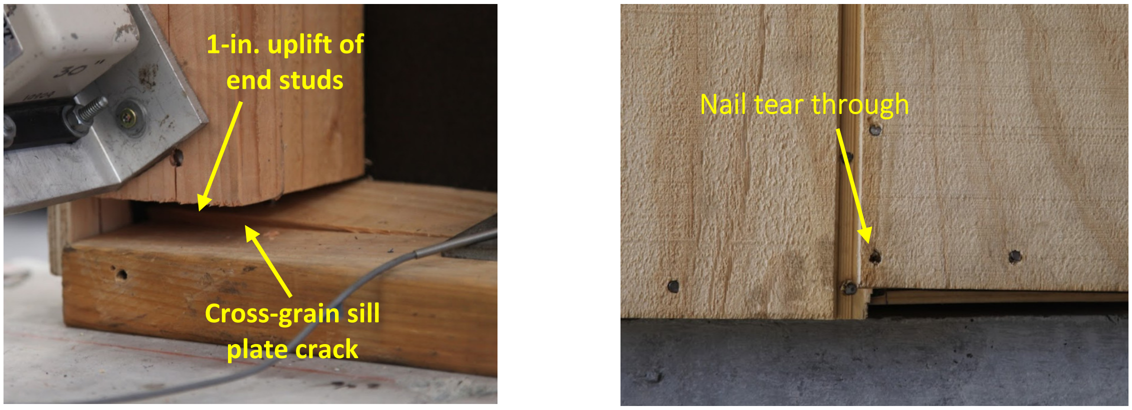


Figure 4.16 **Damage to the dry finished retrofitted 6-ft-tall specimens at lateral strength, drift values are noted: (a) top of north-end interior of Specimen A-14 at +5% drift ratio; (b) bottom of north-end interior of Specimen A-14 at -6% drift ratio; (c) top of north-end interior of Specimen A-14 at -6% drift; (d) bottom of exterior (south and middle panels) of Specimen A-24 at -3% drift ratio; (e) bottom of north-end interior Specimen A-24 at -2% drift ratio; and (f) bottom of exterior of Specimen A-24 (south and middle panels) at -2% drift ratio.**



(e) (f)

Figure 4.16 (continued).

4.4 DAMAGE CHARACTERISTICS POST-STRENGTH

The damage state at 20% residual strength or an 80% reduction in strength post-peak is important in understanding the state of the cripple wall near failure. Not all cripple wall specimens observed a reduction following strength of 80% in load. Those cases will be noted in the following subsections. When an 80% loss of strength in the cripple wall occurred, the loading protocol called for a monotonic push to be imposed for the subsequent drift amplitude. At this point, sufficient residual strength characteristics had been defined for the wall. As such, this section documents the evolution of damage from the displacement level after peak strength had occurred to the displacement level that corresponded to an 80% drop in strength.

4.4.1 Post-Strength Performance of Existing Cripple Walls

Two-Foot-Tall Specimens

Figure 4.17 provides photographs of the post-strength wet finished retrofitted 2-ft-tall specimens at various drift amplitudes. Figure 4.18 provides the same photographs for the dry finished retrofitted 2-ft-tall specimens. The drift amplitudes, percent of post-strength, and specimen name are given in the caption. For all wet finished specimens, the stucco had detached from the framing up most of the height of the stud. In many instances, the only attachment remaining between the stucco and the framing was at the top plates. This can be seen by the large crack formed at the corner of the stucco over horizontal sheathing specimen shown in Figure 4.17(d). At these large displacement amplitudes, the corner finishes had detached from the framing around the same distance as the stucco on the exterior face; see Figure 4.17(c), (d), and (f). For the stucco over framing finished cripple wall, there was little visible damage along the interior of the specimens; see Figure 4.17(e).

All of the wet and dry finished specimens with diagonal sheathing had fractured anchor bolts and large cross-grain splits in the sill plate; see Figure 4.18(a) and Figure 4.18(b). The residual capacity for these cripple walls was nearly fully attributed to the frictional resistance between the sill plate and the foundation; therefore, most of the imposed displacement was seen as displacement of the sill plate relative to the foundation; see Figure 4.18(a) and Figure 4.18(b). The horizontal siding finished cripple wall showed little visible damage on both the interior and exterior face. As with these specimens at strength, the most notable observation was the displacement of the siding boards relative to each other; see Figure 4.18(e). In addition, the horizontal siding finished cripple wall had the smallest drop in load from peak of any specimen by the end of the cyclic portion of the test. For the T1-11 finished cripple walls, the panels detached from the sill plate and for much of the height of the studs, which was similar to the stucco finished cripple walls; see Figure 4.18(c) and (d).

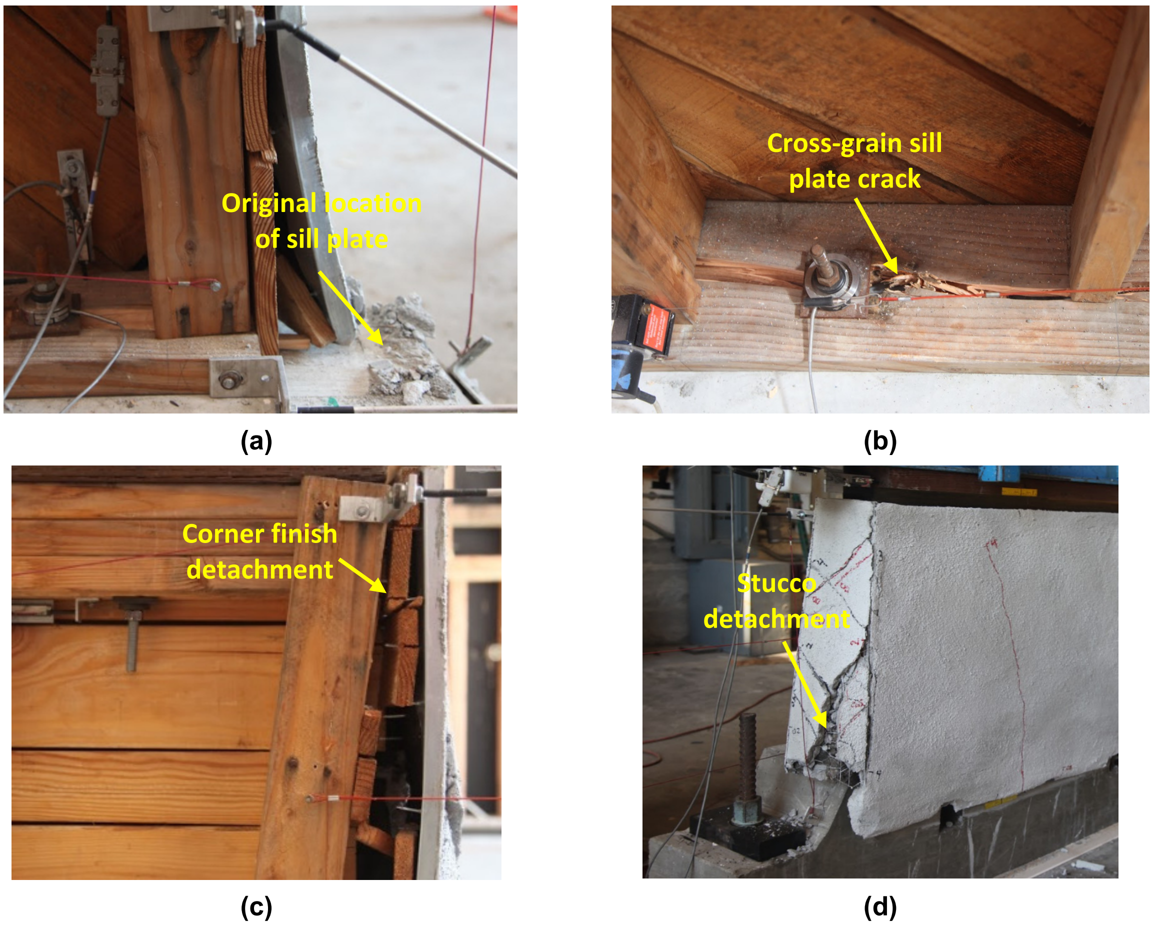
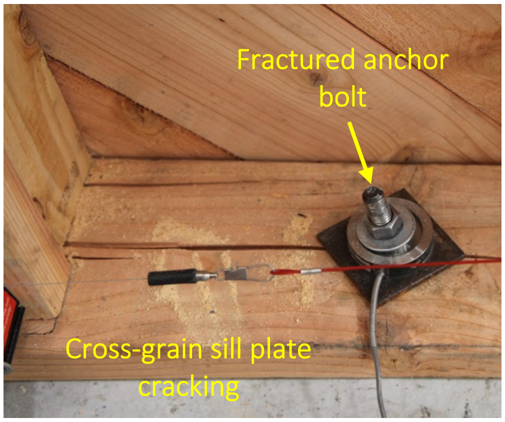


Figure 4.17 Damage to the wet finished retrofitted 2-ft-tall specimens at lateral strength. Drift values are noted: (a) bottom of south-end exterior corner of Specimen A-15 at -13% drift ratio (70% post-strength reduction); (b) bottom of south-end interior of Specimen A-15 at +13% drift ratio (70% post-strength reduction); (c) top of south-end interior of Specimen A-20 at -14% drift ratio (80% post-strength reduction); (d) south-end exterior corner of Specimen A-20 at -14% drift ratio (80% post-strength reduction); (e) north-end interior of Specimen A-17 at +8% drift ratio (80% post-strength reduction); and (f) south-end interior of Specimen A-17 at +8% drift ratio (80% post-strength reduction).

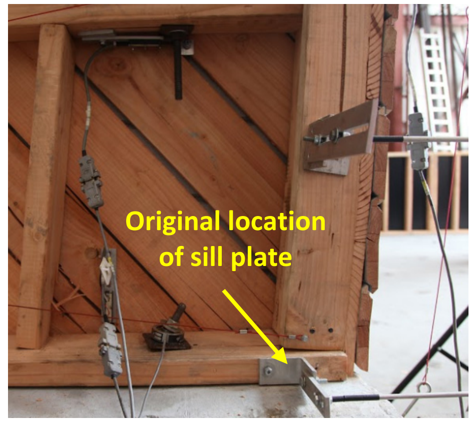

(e)


(f)

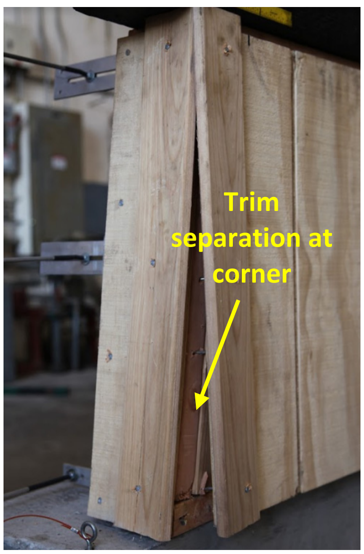
Figure 4.17 (continued).



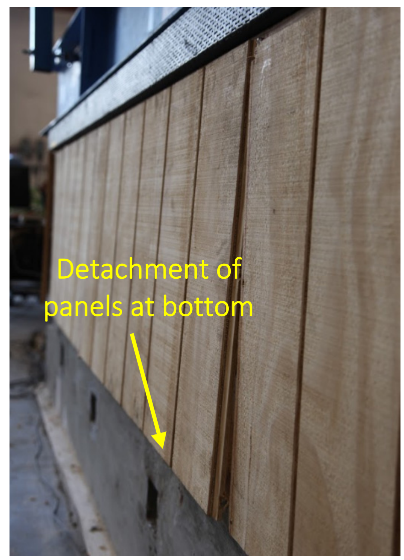
(a)



(b)

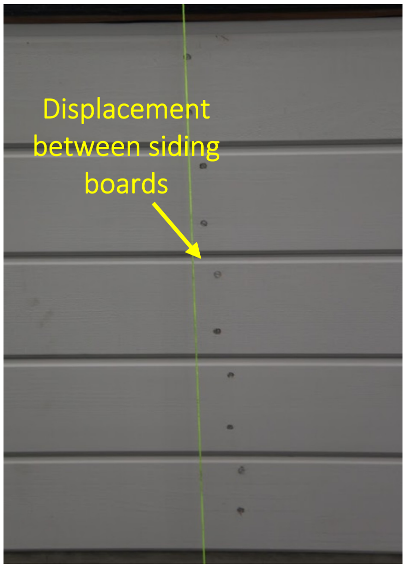


(c)

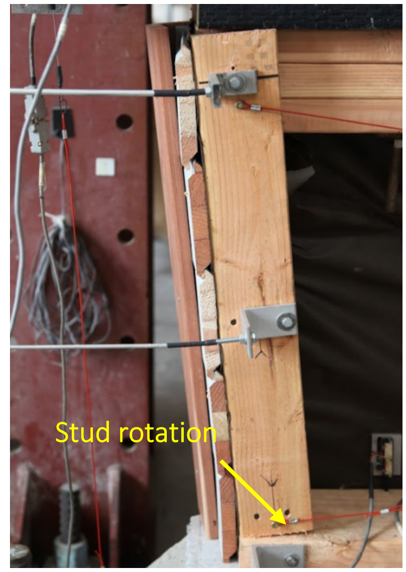


(d)

Figure 4.18 Damage to the dry finished existing 2-ft-tall specimens at lateral strength. Drift values are noted: (a) bottom of middle interior of Specimen A-9 at +12% drift ratio (80% post-strength reduction); (b) bottom of north-end interior Specimen A-9 at +12% drift ratio (80% post-strength reduction); (c) south-end exterior corner of Specimen A-11 at -9% drift ratio (80% post-strength reduction); (d) exterior view of wall looking south of Specimen A-11 at -9% drift ratio (80% post-strength reduction); (e) middle exterior of Specimen A-7 at -12% drift ratio (60% post-strength reduction); and (f) south-end interior of Specimen A-7 at +11% drift ratio (60% post-strength reduction).



(e)

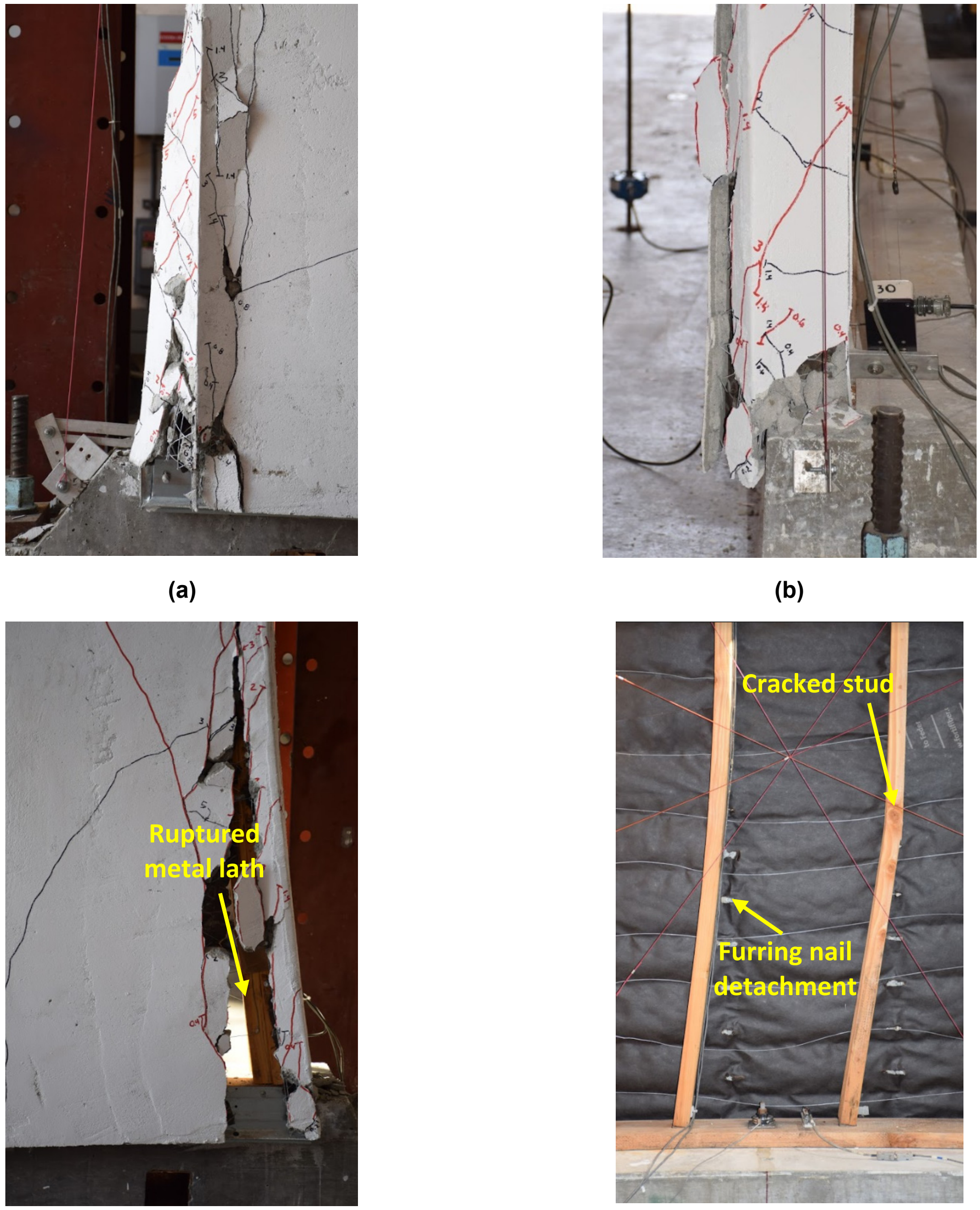


(f)

Figure 4.18 (continued).

Six-Foot-Tall Specimens

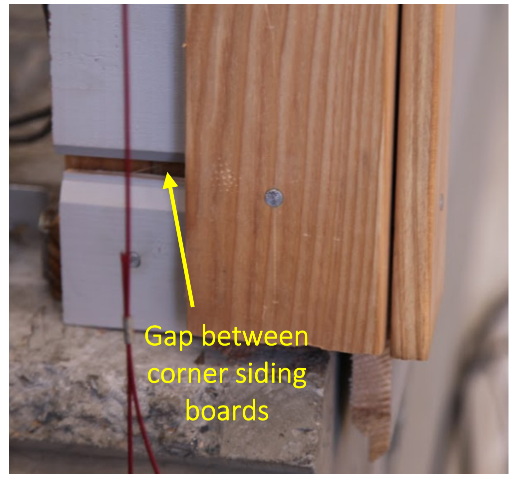
Figure 4.19 provides photographs of the existing wet finished 6-ft-tall specimens at various drift amplitudes, post-strength. Figure 4.20 provides the same photographs for the dry finished existing 6-ft-tall specimens. The drop in strength for the existing 6-ft-tall specimen with stucco over framing finish occurred slightly earlier than the existing 2-ft-tall cripple walls with stucco; see Specimen A-17 and A-22. The damage characteristics were similar in many respects to the shorter cripple walls. The stucco finish had detached from most of the furring nails on the studs and remained only attached to the furring nails at the top plates and the top third of the studs. The large crack openings in the stucco at the corners are shown in Figure 4.19(a), (b), and (c). The stucco had fully detached from the bottom two-thirds of the corners at both ends of the specimen. Along the interior, the studs were bent, and one of the studs had fractured; see Figure 4.19(d). For the 6-ft-tall specimen finished with T1-11 wood structural panels, the panels detached from the sill plate and then continued to detach up the studs. Eventually the detachment of the panels on the studs was extensive enough that the studs underlying panel had almost no contact with the overlying panel; see Figure 4.20(d). Most of the nails at the sill plate and near the base of the studs pulled through or torn through the edges of the T1-11 panels. Higher up on the wall, more nails remained attached to the panels and had pulled out from the framing. The rotation of the studs at the interface with both the top plates and the sill plates were heavily rotated, both in and out of plane. The trim boards at the finish face of the corner had almost fully detached from the framing and only remained partially fastened to the T1-11 panels; see Figure 4.20(f). Along the exterior face, multiple edges of the panels had partially or completely lost attachment to the framing; see Figure 4.20(e).



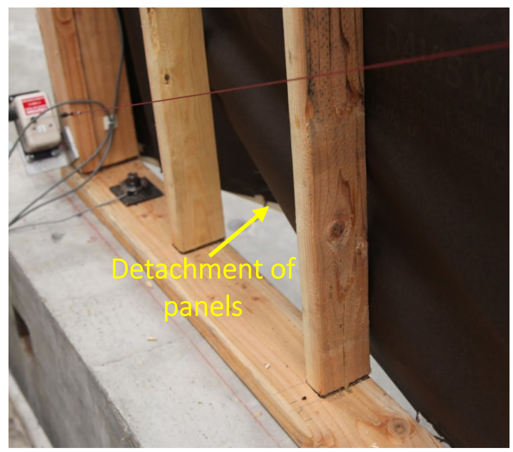
(a) (b)

(c) (d)

Figure 4.19 Damage to the wet finished existing 6-ft-tall specimens at lateral strength. Drift values are noted: (a) bottom of south-end exterior corner of Specimen A-23 at -7% drift ratio (80% post-peak strength reduction); (b) bottom of north-end corner of Specimen A-23 at -7% drift ratio (80% post-peak strength reduction); (c) bottom of north-end exterior of Specimen A-23 at -7% drift ratio (80% post-peak strength reduction); and (d) middle interior of Specimen A-23 at +7% drift ratio (80% post-peak strength reduction).



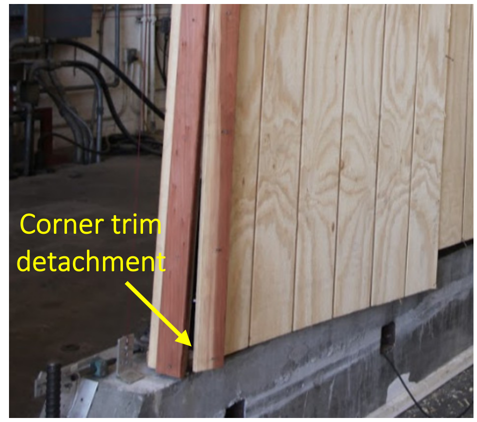
(a) (b)



(c) (d)

Figure 4.20 **Damage to the dry finished existing 6-ft-tall specimens at lateral strength. Drift values are noted: (a) middle exterior of Specimen A-13 at -12% drift ratio (10% post-peak strength reduction); (b) bottom of south-end corner Specimen A-13 at -12% drift ratio (10% post-peak strength reduction); (c) north-end exterior of Specimen A-13 at +11% drift ratio (10% post-peak strength reduction); (d) bottom interior of Specimen A-23 at +10% drift (south and middle panels) (80% post-peak strength reduction); (e) exterior isometric view of Specimen A-23 at -10% drift (80% post-peak strength reduction); and (f) bottom of south-end of Specimen A-23 at -10% drift (80% post-peak strength reduction).**

(e)



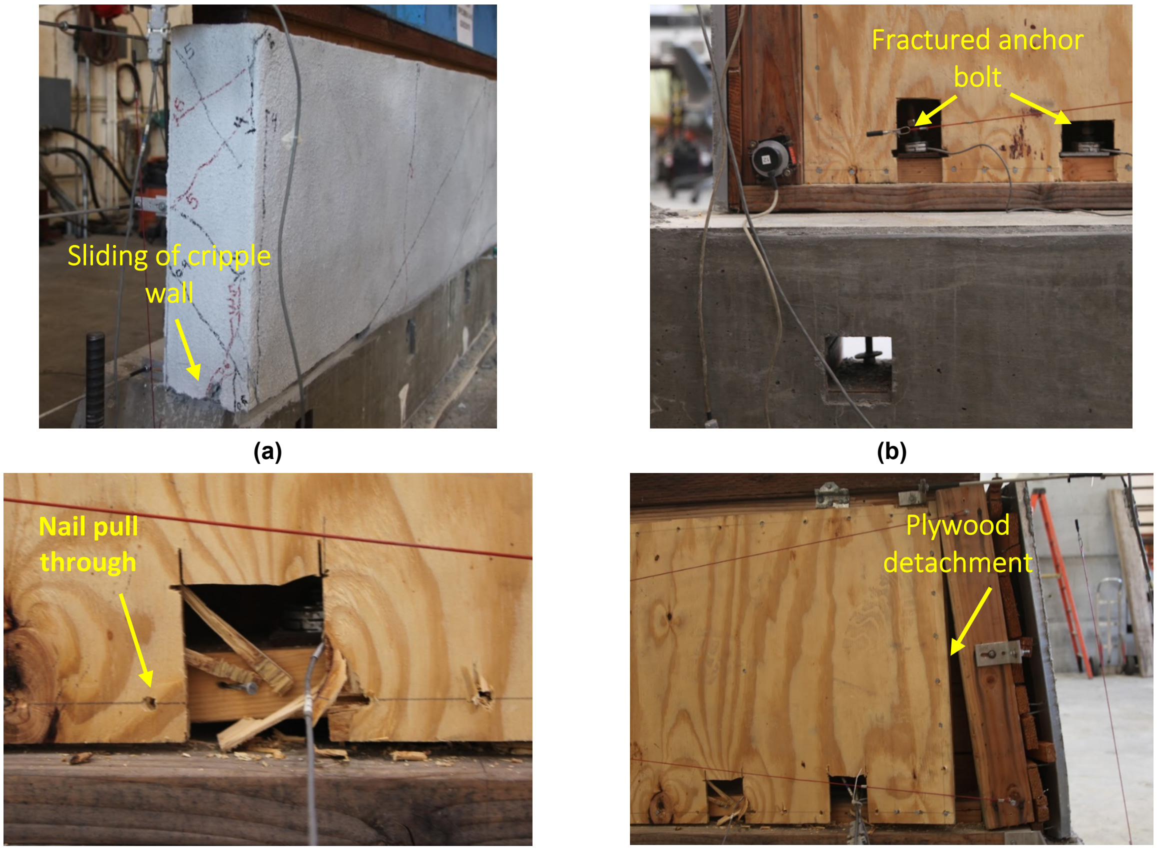
(f)

Figure 4.20 (continued).

4.4.2 Post-Strength Performance of Retrofitted Cripple Walls

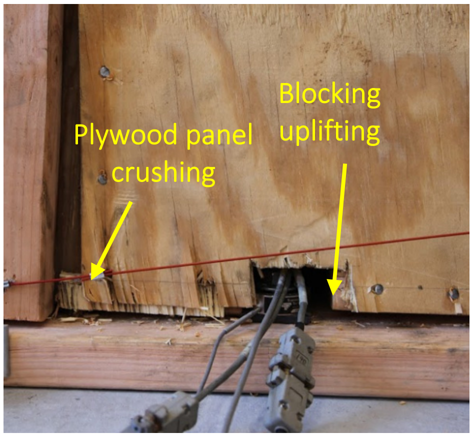
Two-Foot-Tall Specimens

Figure 4.21 provides photographs of the wet finished retrofitted 2-ft-tall specimens at various drift amplitudes, post-strength. Figure provides the same photographs for the dry finished retrofitted 2-ft-tall specimens. The damage to the retrofitted specimen was similar for most specimens. The T1-11 finished cripple walls had different observable damage due to there being no additional plywood with the retrofit. The corners of the plywood crushed against the sill plate and flat studs. Often this resulted in the flat stud being push out laterally or twisting; see Figure 4.22(b). The residual state of the specimen was a result of the plywood partially or fully detaching from the framing on multiple sides; see Figure 4.21(c) and (d). Along the edges of the panels, many of the nails had torn through, especially at the locations where the plywood panels were crushed; see Figure 4.21(a) and (b) There was significantly less damage to both the wet and dry finished specimens with diagonal sheathing; see Figure 4.21(b) and Figure 4.22(c). This was a result of the anchor bolt fracturing, so the residual strength was provided by the frictional resistance of the sill plate sliding along the foundation, a similar mechanism experienced by the existing specimens with diagonal sheathing. For the cripple walls finished with T1-11 wood structural panels, the panels detached along multiple edges; see Figure 4.22(e). The stucco on the wet finished specimens showed the same damage characteristics as the existing wet finished specimens, including large crack openings at the corners where the stucco had detached from the studs up most of the height of the studs. In addition, the finish materials had detached at the corners in a similar fashion, as shown in Figure 4.21(d).

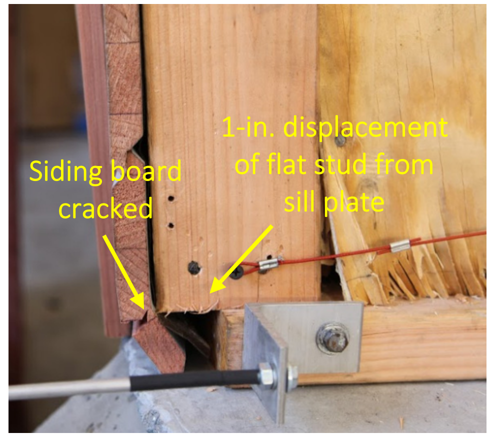


(a) (b) (c) (d)

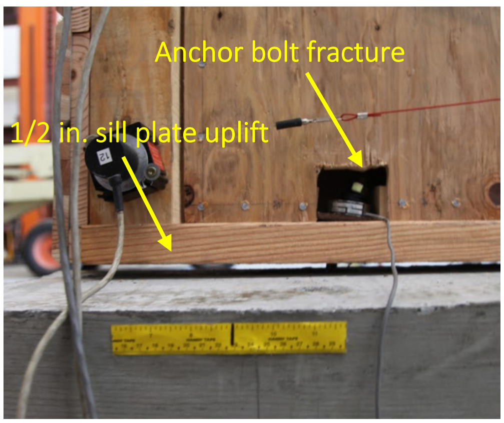
Figure 4.21 **Damage to wet finished retrofitted 2-ft-tall specimens at lateral strength. Drift values are noted: (a) south-end exterior corner of Specimen A-16 at -9% drift ratio (80% post-peak strength); (b) bottom of north-end interior of Specimen A-16 at -9% drift ratio (80% post-peak strength); (c) south-end interior of Specimen A-19 at -12% drift ratio (80% post-peak strength); and (d) bottom interior of Specimen A-19 at -12% drift ratio (80% post-peak strength).**



(a)



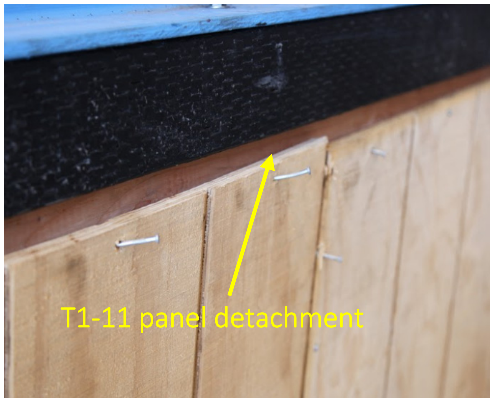
(b)



(c)

(d)

Figure 4.22 **Damage to the dry finished retrofitted 2-ft-tall specimens at lateral strength. Drift values are noted: (a) bottom of south-end interior of Specimen A-8 at -11% drift ratio (80% post-peak strength); (b) bottom of south-end interior of Specimen A-8 at +12% drift ratio (80% post-peak strength); (c) bottom north-end exterior of Specimen A-10 at +9% drift ratio (80% post-peak strength); (d) middle exterior of Specimen A-10 at +9% drift ratio (80% post-peak strength); (e) top of north-end exterior corner of Specimen A-12 at -9% drift (south and middle panels) (80% post-peak strength); and (f) top of middle exterior of Specimen A-12 at -9% drift (south and middle panels) (80% post-peak strength).**



(e)

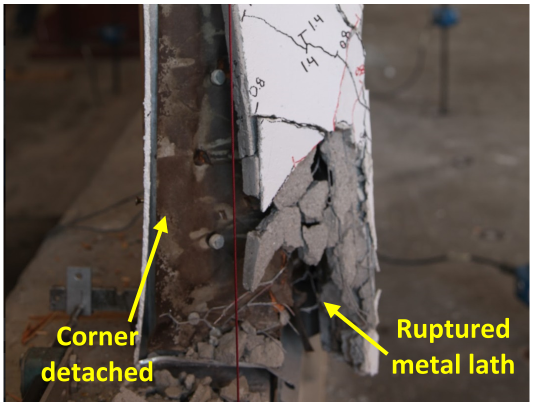
(f)

Figure 4.22 (continued).

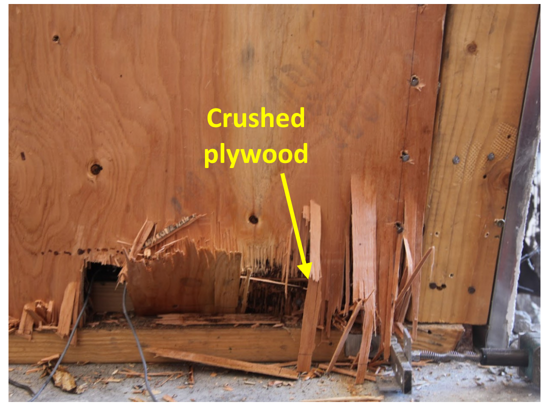
Six-Foot-Tall Specimens

Figure 4.23 provides photographs of the wet finished retrofitted 6-ft-tall specimens at various drift amplitudes, post-strength. Figure 4.24 provides the same photographs for the dry finished retrofitted 6-ft-tall specimens. For the retrofitted 6-ft-tall cripple wall with stucco exterior finish, the stucco finish had detached from most of the furring nails on the studs and remained only attached to the furring nails at the top plates and the top third of the studs, similar to Specimen A-25. The stucco had fully detached from the bottom two-thirds of the corners at both ends of the specimen. The detachment at the bottom of the corners can be seen in Figure 4.23(a). Along the interior, the plywood was heavily damaged. At the ends, the plywood crushed against the flat studs and caused the flat studs to laterally displace; see Figure 4.23(b). At the bottom of the panels, the fasteners either pulled through the panels or tore through the edges of the panels [Figure 4.23(d)], and at the top of the walls, there was assortment of nails withdrawing from the framing, pulling through the plywood, or tearing through the plywood edges; see Figure 4.23(c).

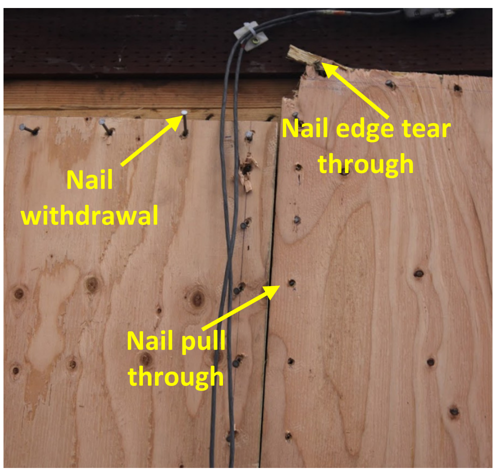
For the retrofitted 6-ft-tall cripple wall with horizontal siding, the detachment of the plywood occurred when the nails pulled through the plywood and remained attached to the framing. At the bottom of the cripple wall, the opposite occurred. The plywood panels remained attached to the nails. Significant uplift of the panels occurred as the blocking either split or was uplifted with the panels; see Figure 4.24(a). Along the studs, there was a combination of nails pulling through the plywood and nails pulling out of the framing, leading to detachment of the plywood panels; see Figure 4.24(b). The large amount of uplift forces was carried in tension by the hold-downs on both ends. Eventually, this caused the stud attaching the hold-down to the framing to split; see Figure 4.24(c). For the retrofitted 6-ft-tall cripple wall with T1-11 wood structural panels, cracking of the sill plate extended nearly two studs bays on both ends of the wall; see Figure 4.24(e). In these photographs, the separation of T1-11 panels from the sill plate can be observed. The nails attached through the 5/8-in. sections of the panels generally pulled out from the framing, while the nails attached through the 5/16 in. sections generally pulled through the panels or tore through the edges of the panels. At the panel overlaps, sections of the T1-11 panels are thin, and the fasteners had pulled through or torn through the panels in most instances, especially near the bottom of the wall. The withdrawal of the fasteners at the sill plate can be seen in Figure 4.24(d). Splitting of one of the studs occurred at 6% drift and led to a large displacement of the stud; see Figure 4.24(f). Previously, there had been visible bending of the studs, leading to the splitting of the stud. The damage characteristics of the 6-ft-tall specimen were similar to the 2-ft-tall specimen, but more pronounced.



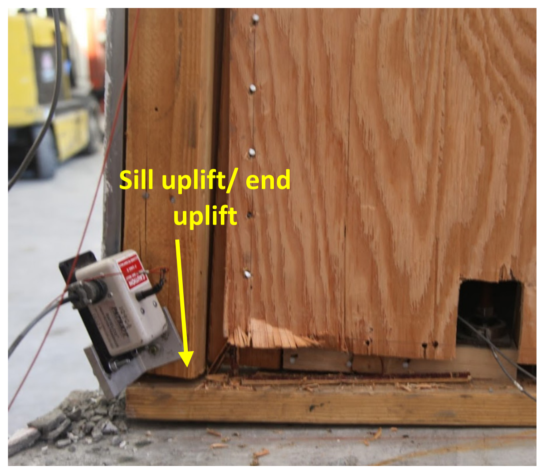
(a)



(b)

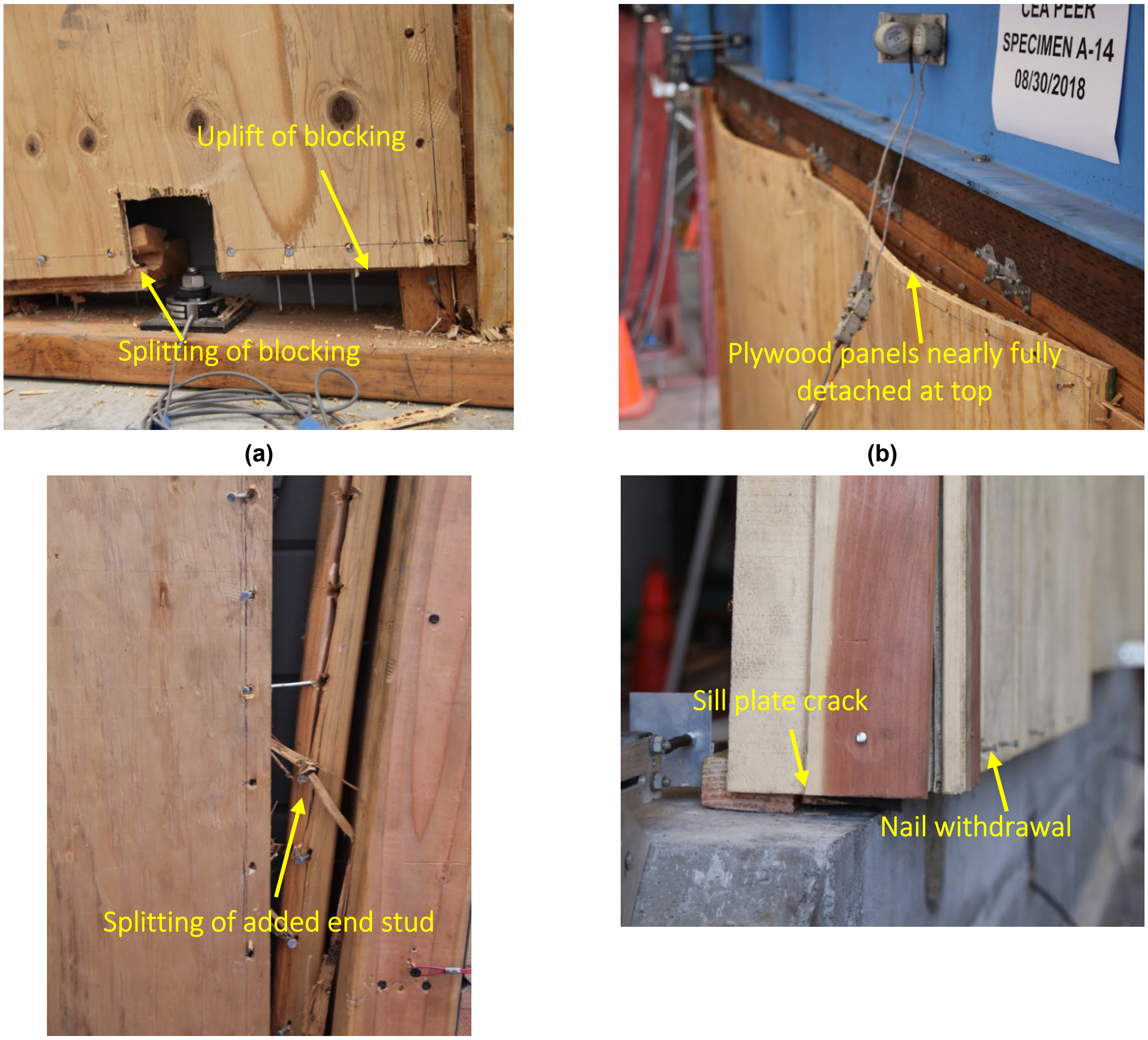


(c)



(d)

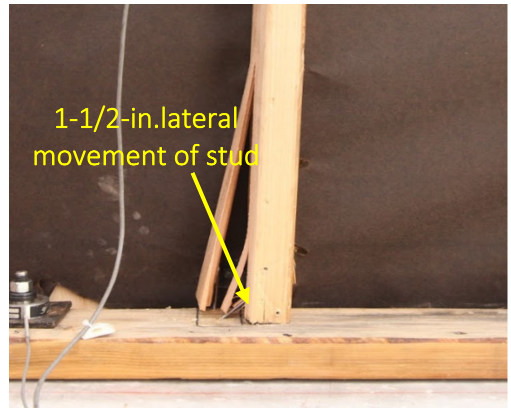
Figure 4.23 **Damage to the wet finished retrofitted 6-ft-tall specimens at lateral strength. Drift values are noted: (a) bottom of south-end corner of Specimen A-24 at +8% drift ratio (80% post-peak strength reduction); (b) bottom of south-end interior of Specimen A-24 at +8% drift ratio (80% post-peak strength reduction); (c) top of middle interior of Specimen A-24 at +8% drift ratio (80% post-peak strength reduction) (south and middle panels); and (d) bottom of north-end interior Specimen A-24 at +8% drift ratio (80% post-peak strength reduction).**



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

Figure 4.24 **Damage to the dry finished retrofitted 6-ft-tall specimens at lateral strength. Drift values are noted: (a) bottom of south-end interior of Specimen A-14 at -10% drift (80% post-peak strength reduction); (b) top of interior of Specimen A-14 at -10% drift (80% post-peak strength reduction) (north and middle panels); (c) bottom of south-end interior Specimen A-14 at +10% drift (80% post-peak strength reduction); (d) bottom of south-end exterior corner of Specimen A-24 at -6% drift (80% post-peak strength reduction); (e) bottom of south-end interior of Specimen A-24 at +6% drift ratio (80% post-peak strength reduction); and (f) bottom of middle interior of Specimen A-24 at -6% drift ratio (80% post-peak strength reduction).**

(e)



(f)

Figure 4.24 (continued).

5 Conclusions

Quantifying the performance of retrofitted and unretrofitted single-family wood-frame houses has become increasingly important in California due to the high seismicity of the state and the often-poor seismic resiliency of some portions of the housing stock. From field observations of past earthquakes, it has been found that inadequate lateral bracing of both cripple walls and sill bolting are the primary reasons for failures of residential homes even in the event of moderate earthquakes. While methods to retrofit weak cripple walls and improve sill anchorage have been developed, the improvement in performance with retrofit have observed only limited experimental quantification. In addition, little knowledge is available to characterize the performance of houses with existing cripple walls and sill anchorages. To this end, this report presents a comparison of results and observations across a large suite of 28 specimens, both wet (stucco) and dry (non-stucco) exterior finishes. The comparisons presented herein are a compendium of the results of a series of three prior test reports, where the response of individual specimens was measured and observed physical damage documented.

The wet exterior finishes studied in this program included stucco over framing, stucco over horizontal lumber sheathing, and stucco over diagonal lumber sheathing, and the dry exterior finishes studied were horizontal shiplap siding, horizontal shiplap siding over diagonal lumber sheathing, and T1-11 wood structural panels. These experiments involved imposition of combined vertical loading and quasi-static reversed cyclic lateral load onto cripple walls 12 ft long and 2 ft or 6 ft high. The anchorage, boundary conditions, and applied vertical load were all held constant for each specimen. In what follows, conclusions specific to the comparison across all specimens are summarized. Readers interested in conclusions across groups of like specimens (such as groups finished with only stucco or groups finished with only dry materials) may consult the reports of Schiller et al. [2020(a-c)].

5.1 GENERAL OBSERVATIONS

- The hysteresis of all specimens, regardless of dry or wet finish, was generally stable with no abrupt brittle failure, although the strength and stiffness of the unretrofitted specimens were much smaller compared to the retrofitted specimens; and
- The response of the unretrofitted specimens with the wet finish was dominated by the detachment of stucco from the furring nails, which precipitated at the sill-framing connection. In contrast, the response of the dry finished existing

specimen was dominated by the behavior of nailing of the dry finish material. Although this damage precipitated at the lower regions of the wall, it tended to be more distributed across the wall face and wall ends.

5.2 IMPACT OF EXTERIOR FINISH

5.2.1 Lateral Strength of Existing Specimens

- For existing 2-ft-tall cripple walls, the horizontal siding was the weakest exterior finish tested. Its strength was around 30% of the lateral strength of the next weakest existing 2-ft-tall specimen, which was finished with stucco over framing;
- For existing 6-ft-tall cripple walls, horizontal siding was again the weakest exterior finish tested as well as the weakest of any specimen tested. The existing 6-ft-tall specimen had around 55% of the capacity of the 2-ft-tall specimen. Compared with the other 6-ft-tall specimens, the cripple wall with the horizontal siding finish had 25% of the capacity of the T1-11 finished specimen and 15% of the capacity of the stucco over framing finished specimen;
- The finish with horizonal siding over diagonal sheathing was the strongest exterior finish tested amongst all dry and wet finished specimens. This exterior finish was 40% stronger than the stucco over diagonal sheathing exterior finish. Both specimens had push loading strength within 10% of the other, but the horizontal siding over diagonal sheathing specimen was 75% stronger in the pull loading direction. The stucco over diagonal sheathing specimen was around 10% stronger in the push loading direction, which would not have been expected due to the orientation of the sheathing boards. However, the finish materials were not able to achieve full strength due to a large cross-grain crack propagating across the entire sill plate that resulted in a loss of strength;
- Amongst all the existing 2-ft-tall specimens, the strengths of stucco over framing, T1-11 wood structural panels and stucco over horizontal sheathing specimens were within 5% of each other, with an average of about 550 plf; and
- The stucco over framing finished 6-ft-tall specimen was on average 70% stronger than the T1-11 finished specimen in both loading directions.

5.2.2 Lateral Strength of Retrofitted Specimens

- For the retrofitted 2-ft-tall cripple walls, T1-11 wood structural panels were the weakest exterior finish amongst all dry and wet finished specimens, with an average lateral strength of about 1100 plf. The retrofitted T1-11 finished specimen attained 60% of the strength compared to the stucco over framing retrofitted specimen, which had the next weakest performance;
- For the retrofitted 6-ft-tall cripple walls, T1-11 wood structural panels were also the weakest exterior finish, with an average lateral strength of 850 plf or about 50% that of the horizontal siding retrofitted specimen;

- Amongst all specimens, the horizontal siding over diagonal sheathing finish was the strongest retrofitted specimen, with an average lateral strength of 2550 plf. The strength of this specimen was 15% larger than the specimen finished with stucco over diagonal sheathing, which had the next strongest performance. Both specimens with diagonal sheathing experienced anchor bolt fractures, resulting in a loss of strength. Therefore, it would be expected that the strength of both specimens would have increased if additional anchor bolts had been used;
- The average lateral strength of the retrofitted 2-ft-tall cripple walls with the stucco finish versus the horizontal siding finish were nearly identical at about 1800 plf;
- For the retrofitted 6-ft-tall specimens, the stucco finished cripple wall was comparable in strength with the horizontal siding finished specimen. Indicating that the presence of the retrofit dictated the strength characteristics rather than the type of exterior finish. In addition, the capacity of the like specimen pair after retrofit (the 2-ft-tall and 6-ft-tall specimens) were nearly identical; and
- The lateral strength in the push and pull loading direction for all retrofitted 2-ft-tall specimens, irrespective of finish type, were nominally symmetric. For the retrofitted 6-ft-tall specimens, the lateral strengths were similarly symmetric and nominally within about 10% of each other.

5.2.3 Drift Capacity of Existing Specimens

- In terms of the relative displacement response, the existing wet specimens attained strength at lower drift amplitudes than the existing dry finished specimens, between 1.1% to 2.5% relative drift versus 4.0% to 5.2% relative drift, respectively;
- The stucco over framing finish had the lowest drift capacity of all exterior finishes tested, achieving strength at 1.2% relative drift. The stucco finished specimen reached 40% post-peak strength at 4.5% relative drift, which was the lowest for all 2-ft-tall specimens. For the 6-ft-tall specimen, lateral strength was reached at 1.1% relative drift. In addition, 40% post-peak strength was reached at 5.0% relative drift, which was the earliest of any of the 6-ft-tall specimens. The stucco finished cripple walls reached strength at earlier drift amplitudes than any other specimens tested;
- Horizontal siding had the largest drift capacity, achieving strength at 4.0% relative drift and 40% post-peak strength at 10.5% drift, for the 2-ft-tall specimen. For the 6-ft-tall specimen, lateral strength was reached at 11.5% relative drift and lacked development of more than a 10% reduction in strength;
- The drift capacity at strength of the T1-11 finish and stucco over horizontal sheathing finished 2-ft-tall specimens were the most similar to each other of any wet and dry finished specimens. The relative drift ratio at 40% post-peak strength was 7.7% for the stucco over horizontal sheathing finished specimen and 8.0% for the T1-11 finished specimen, however, the T1-11 finished

specimen reached strength at nearly twice the relative drift ratio of the stucco over horizontal sheathing specimen (4.7% versus 2.4% relative drift ratio); and

- For the 6-ft-tall specimens, the drift capacity of the T1-11 and stucco finished specimens were the most similar. The stucco finished specimen reached strength at 1.1% relative drift ratio, and the T1-11 finished specimen reached strength at 2.5% relative drift ratio. While the relative drift at strength were significantly different, the stucco finished specimen reached 80% of pre-peak strength at 0.6% relative drift and 40% post-peak strength at 5.0% relative drift. These values for the T1-11 finished cripple wall were 0.7% and 6.0% relative drift, respectively.

5.2.4 Drift Capacity of Retrofitted Specimens

- In terms of the relative displacement response, the retrofitted wet specimens attained strength from 2.9% to 5.3% relative drift. For the dry finished retrofitted specimens, strength was achieved from 2.0% to 6.4% relative drift;
- For the 2-ft-tall specimens, the retrofit horizontal siding finished cripple wall had the largest drift capacity, achieving strength at 6.1% relative drift. In addition, the specimen reached 80% pre-peak strength at 2.3% relative drift and 40% post-peak strength at 10.5% relative drift. The range in drift amplitudes from 80% pre-peak strength to 40% post-peak strength was similar to the stucco (1.3% and 9.3% relative drift), stucco over horizontal sheathing (2.2% and 9.6% relative drift), and T1-11 (1.9% and 9.4% relative drift) finished specimens. This indicates that the applied retrofit dominated the response of all cripple walls;
- The retrofitted specimens with diagonal sheathing were the only specimen to fail due to either cross-grain cracking of the sill plate and/or fracturing of the anchor bolts. Due to this, the response was close to symmetric for the existing 2-ft-tall specimens when it would be expected that the strength in the pull loading direction would have been greater than the strength in the push loading direction. This is expected because of the orientation of the diagonal sheathing boards. Namely, as observed for the existing diagonally sheathed specimens, the gaps between the sheathing boards closed in one direction, while in the opposing direction, the sheathing boards bore on each other, providing additional resistance. In this sense, when retrofit is applied, the finish material of diagonal sheathing is not fully mobilized; and
- Stucco over diagonal sheathing cripple walls experienced the most uplift of any of the finishes. In addition, the uplift was significantly larger in the push loading direction due to the orientation of the sheathing boards, displacing both laterally and upward during pull loading.

5.3 RELATIVE IMPACT OF SPECIMENS RETROFITTED ACCORDING TO *FEMA P-1100* GUIDELINES

- All cripple walls retrofitted according to the *FEMA P-1100* guidelines showed increased strength, stiffness, and energy dissipation for all tested cripple walls, irrespective of an existing condition or wet or dry finishes. In some cases, the retrofit increased the drift capacity of the cripple wall;
- The lowest increase in strength for retrofitted specimens occurred with the horizontal siding over diagonal sheathing cripple walls, with an average strength increase of over 80% observed (1435 plf to 2550 plf). It is difficult to determine what the increase in strength would have been if the stucco over diagonal sheathing finished specimens had not experienced anchor bolt fracture and subsequent cross-grain induced cracking in the sill plate. Despite this failure mechanism, the percent increase in strength for the stucco over diagonal sheathing cripple wall was 115% (1027 plf to 2200 plf);
- The largest increase in lateral strength was observed for those retrofitted specimens with a horizontal siding finish. The retrofitted 2-ft-tall specimen was almost ten times as strong as the comparably finished existing specimen (172 plf to 1831 plf), and the retrofitted 6-ft-tall specimen was almost twenty times as strong as the existing specimen (93 plf to 1770 plf);
- Besides the horizontal siding specimens, the wet finished retrofitted specimens saw the largest increases in strength, on average between 115% and 260%. The stucco finished specimen retrofitted 2-ft-tall increased in strength about 230% (551 plf to 1815 plf), and the stucco horizontal sheathing finished 2-ft-tall specimen increased in strength by around 260% (569 plf to 2037 plf);
- The smallest increase in initial stiffness associated with the relative drift at 80% pre-peak strength occurred with the stucco over framing finished cripple walls. For the 2-ft-tall specimens, the increase was around 25%; for the 6-ft-tall specimens it was around 60%. For the T1-11 finished 6-ft-tall cripple wall, the stiffness also increased by around 60%;
- The largest increase in initial stiffness was for the 6-ft-tall specimen with the horizontal siding finish. The retrofitted specimen experienced about a thirty-fold increase in stiffness, compared with around a one-and-a-half-fold increase in stiffness for the 2-ft-tall specimens;
- The increase in initial stiffness was similar for both the horizontal siding over diagonal sheathing and stucco over diagonal sheathing specimens in both loading directions, with a 90% and 95% increase in the push loading direction and a 167% and 161% increase in the pull loading direction, respectively;
- The drift capacity increased the most for the stucco over framing finished retrofitted specimens. For the 2-ft-tall cripple walls, the drift at strength increased from 1.3% to 4.8% relative drift ratio, and the relative drift ratio at 40% post-peak strength increased from 4.6% to 9.3%. For the 6-ft-tall

specimens, the relative drift ratio at strength increased from 1.1% to 2.9%, and the relative drift ratio at 40% post-peak strength increased from 5.0% to 7.1%;

- The drift capacity decreased for horizontal siding finished specimens as well as specimens finished with horizontal siding over diagonal sheathing and stucco over diagonal sheathing. The drift capacity remained about the same for T1-11 finished retrofitted 6-ft-tall cripple wall;
- The largest increase in the dissipation of cumulative energy at 40% post-peak strength was nearly fifteen-fold for the stucco finished retrofitted 2-ft-tall cripple walls;
- The largest increase in the dissipation of cumulative energy was for dry finished specimens finished with horizontal siding. The 2-ft-tall specimen experienced a seven-fold increase at 40% post-peak strength, and the 6-ft-tall specimen experienced a five-fold increase at lateral strength. Because the existing 6-ft-tall specimen did not have a 60% loss of strength during testing, the comparison was made of its lateral strength; and
- The smallest increase in cumulative energy dissipated was for those finished with T1-11 wood structural panels. The cumulative energy dissipated at 40% post-peak strength for both the retrofitted 2-ft-tall and the 6-ft-tall specimens was 2.5 times that of the existing specimens.

5.4 DAMAGE CHARACTERISTICS

- For wet finished specimens, the specimen's physical behavior in low drift amplitudes (0.2–1.4%) was dominated by cracking and crushing of stucco. Cracking of the stucco was minimal on the face of the cripple walls, whereas corners finished with stucco experienced significant cracking that propagated vertically and diagonally at the corners, even at low drift amplitudes (0.2%–1.4% drift amplitude). The extent of cracking and crack widths increased as the imposed drift increased. For cripple walls with corner conditions at large drift amplitudes, crushing and spalling of the stucco was observed, particularly at the interface with the concrete foundation;
- In contrast, for dry finished specimens, nail rotation, pullout and pull through dominated the damage development in the early drift cycles and increased at larger drift amplitudes. The highest concentration of damage to components of the dry finished specimens, occurred at the corners, where vertical trim boards finished the specimens. For wet specimens after strength was attained, the lateral resistance contribution from the stucco was greatly reduced due to loss of its connection to the sheathing and/or framing members (i.e., furring nail detachment);
- Regardless of wet or dry finish, failure of the retrofitted cripple walls was primarily attributed to plywood sheathing nail head pull through and/or nail withdrawal along the edges of the plywood panels, especially along the top plate and sides. At the bottom of the plywood panels, nails withdrew from the

framing and/or pulled over the plywood panels, with the added blocking splitting at large displacements. Some tearing of the nails through the plywood panels (edge tear-out) was observed at the corners. Damage to the finish materials occurred at larger drift amplitudes after experiencing significant damage to the components of the retrofit; and

- The T1-11 finished specimens exhibited similar damage characteristics as the plywood panels of the retrofitted cripple walls. At large displacements, the T1-11 panels would "skirt out" as they detached from the sill plate and bottom of the studs, while remaining attached to the upper top plates. This was similar to what was observed at large displacements with the stucco on the wet finished specimens.

REFERENCES

Cobeen K., Mahdavifar V., Hutchinson T.C., Schiller B., Welch D.P., Kang, G.S., Bozorgnia, Y. (2020). Large-component seismic testing for existing and retrofit single-family wood frame dwellings, *PEER Report No. 2020/20*, Pacific Earthquake Engineering Research Center, Berkeley, CA.

FEMA (2018). *Vulnerability-Based Seismic Assessment and Retrofit of One- and Two-Family Dwellings, FEMA P-1100,* Vol. 1, Prestandard, Federal Emergency Management Agency, Washington, DC.

Schiller B., Hutchinson T.C., Cobeen K. (2020a). Cripple wall small-component test program: Wet specimens I, *PEER Report No. 2020/16*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

Schiller B., Hutchinson T.C., Cobeen, K. (2020b). Cripple wall small-component test program: Dry specimens, *PEER Report No. 2020/17*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

Schiller B., and Hutchinson T.C., Cobeen, K. (2020c). Cripple wall small-component test program: Wet specimens II, *PEER Report No. 2020/18*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

Schiller B., Hutchinson T.C., Cobeen K. (2020d). Cripple wall small-component test program: comparisons, *PEER Report No. 2020/19*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

Zareian F., Lanning J. (2020). Development of testing protocol for cripple walls, *PEER Report No. 2020/15*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

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