PACIFIC EARTHQUAKE ENGINEERING
RESEARCH CENTER

Cripple Wall Small-Component Test Program: Wet Specimens II

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 2020/18

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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 retrofitted and existing cripple walls. This report focuses stucco or "wet" exterior finishes. Paralleled by a large-component test program conducted at the University of California, Berkeley (UC Berkeley) [Cobeen et al. 2020], the present study involves two of multiple phases of small-component tests conducted at the University of California San Diego (UC San Diego). Details representative of era-specific construction, specifically the most vulnerable pre-1960s construction, are of predominant focus in the present effort. Parameters examined are cripple wall height, finish style, gravity load, boundary conditions, anchorage, and deterioration. This report addresses the third phase of testing, which consisted of eight specimens, as well as half of the fourth phase of testing, which consisted of six specimens where three will be discussed. Although conducted in different phases, their results are combined here to co-locate observations regarding the behavior of the second phase the wet (stucco) finished specimens. The results of first phase of wet specimen tests were presented in Schiller et al. [2020(a)]. Experiments involved imposition of combined vertical loading and quasi-static reversed cyclic lateral load onto ten cripple walls of 12 ft long and 2 or 6 ft high. One cripple wall was tested with a monotonic loading protocol. All specimens in this report were constructed with the same boundary conditions on the top and corners of the walls as well as being 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), cripple wall height, loading protocol, anchorage condition, boundary condition at the bottom of the walls, and the retrofitted condition. Details of the test specimens, testing protocol, including instrumentation; and measured as well as physical observations are summarized in this report. Companion reports present phases of the tests considering, amongst other variables, impacts of various boundary conditions, stucco (wet) and non-stucco (dry) finishes, vertical load,

cripple wall height, and anchorage condition. Results from these experiments are intended to support advancement of numerical modeling tools, which ultimately will inform seismic loss models capable of quantifying the reduction of loss achieved by applying state-of-practice retrofit methods as identified in *FEMA P-1100, Vulnerability-Base Seismic Assessment and Retrofit of One- and Two-Family Dwellings*.

ACKNOWLEDGMENT AND DISCLAIMER

ACKNOWLEDGMENT

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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 CEA, Pacific Earthquake Engineering Research Center (PEER), members of the Project Team, or the Regents of the University of California.

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1 Introduction

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 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 and 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 focused on the first phase of an experimental investigation to study the seismic performance of retrofitted and existing cripple walls with sill anchorage. All tests discussed in this report were finished with stucco or “wet” materials. Paralleled by a large-component test program conducted at University of California, Berkeley (UC Berkeley) [Cobeen et al. 2020], the present study involves the third and a portion of the fourth phase of the four phases of small-component tests conducted at the University of California San Diego (UC San Diego).

The report titled *Cripple Wall Small-Component Test Program: Wet Specimens I*, described the strategy for characterizing the primary variables and their ranges for the small cripple wall test program at UC San Diego. In addition, the background and motivation for the study was presented, field observations from past cripple wall failures and previous research on the topic reported, and details of the selection process for the loading protocol explained [Schiller et al. 2020(a)]. Thus, the present report summarizes only the salient features of the program as well as specific differences with respect to the scope of the specimens reported herein.

1.2 UC SAN DIEGO TEST PROGRAM

The small-component test program at UC San Diego was divided into four phases, with six–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 contained 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 or retrofit 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)];
- *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, one pair being 2 ft tall and the other being 6 ft tall. 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 retrofitted walls built upon knowledge gained in Phase 1 regarding the effectiveness of the *FEMA P-1100* prescriptive retrofit guidelines [Schiller et al. 2020(b)];

- *Phase 3.* The third phase of testing also consisted of eight specimens. These specimens were each 2 ft tall with the same boundary conditions imposed on the top and ends of the cripple walls. There were three pairs of identical walls that only differed in their retrofit 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. Pairs of cripple walls with stucco over horizontal lumber sheathing, stucco over diagonal lumber sheathing, and stucco over framing were tested. 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 providing additional results regarding the performance of the *FEMA P-1100* prescriptive retrofit guidelines [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 retrofitted. 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 guidelines. 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 were four phases of testing, the reporting of each phase was not strictly organized based on the testing phase; four reports are available to summarize the UC San Diego small-component test program. Their organization is designed as follows. The first and third reports focus on wet specimens, i.e., specimens with stucco exterior finishes (i.e., Phase 1, Phase 3, and a portion of Phase 4). The second report focuses solely on dry specimens, i.e., specimens finished with wood absent stucco (i.e., Phase 2 and a portion of Phase 4). The final (fourth) report presents a cross comparison of specimens, both wet and dry finishes. 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)]; and
- Report 4: Cripple Wall Small-Component Test Program: Comparisons [Schiller et al. 2020(d)].

1.3 SCOPE OF THIS STUDY AND ORGANIZATION OF REPORT

As with the tests discussed in the previous report, a consistent wall length, framing plan, and foundation setup were utilized for each test. With a focus on wet finished specimens, the present report is organized as follows:

- Chapter 2 presents the test matrix and details of specimens reported specifically in the present report, namely, the second phase of wet finished specimens. Subsequently, the testing setup and loading protocol utilized are described. In addition, visual documentation of the construction of the cripple walls is provided. Finally, the layout of instrumentation used to acquire data for each test is presented;
- Chapter 3 presents the results from each tested specimen. Specifically, the load-deflection response, anchor bolt load histories, relative displacement measurements, distortion within panel segments of the wall specimens, and vertical displacement of the wall are presented;
- Extensive documentation of the physical damage to each cripple wall specimen is provided in Chapter 4. Visually documented damage is correlated with key attributes of the measured load-deflection curves provided in Chapter 3;
- Finally, Chapter 5 provides concluding remarks regarding observations from the wet or stucco test program that were not addressed in the first report; and
- Appendices included in this report document material properties, instrumentation plans, and an expansion of all measured response results for individual specimens.

2 Specimen Details, Test Setup, and Instrumentation

2.1 GENERAL

The focus of this chapter is on the details of the cripple wall specimens, test setup, and testing instrumentation for the second phase of wet (stucco) exterior finished specimens. As described in the previous chapter, many variables were examined in this entire test program. Key parameters of interest in this report include the height, wet exterior finishes, retrofit condition, and loading protocol of the cripple walls. Phase 1 tests involved all wet finished specimens, investigating the effect of various boundary conditions on the top, bottom, and sides of the cripple wall. This allowed for baseline boundary conditions to be used in subsequent testing. Herein, the baseline boundary conditions adopted for all specimens are top boundary condition B and for the majority of specimens are bottom boundary condition “c”. An additional boundary condition for the bottom of the cripple walls, bottom boundary condition “d”, was also investigated. The construction details for all other boundary conditions can be found in the previous report [Schiller et al. 2020(a)].

Three different wet exterior finishes were selected for testing, namely: (1) stucco over framing; (2) stucco over horizontal lumber sheathing; and (3) stucco over diagonal lumber sheathing. All of these finish styles are common to the pre-1945 era of housing construction. Two of the tests considered 6-ft-tall cripple walls finished with stucco over framing, in an existing and retrofit pair. The other nine cripple walls considered 2-ft-tall and constructed with stucco over framing (3), stucco over horizontal sheathing (4), and stucco over diagonal sheathing (2). Four of the specimens were tested in pairs of retrofitted and existing cripple walls to elicit the benefits of retrofitting existing specimens. All specimens were subjected to a heavy vertical load (450 plf), which is representative of a two-story house constructed with heavy building materials. One of the stucco over horizontal sheathing specimens had a wet set sill plate, and another was loaded monotonically. All other specimens had typical sill plates fastened with anchor bolts and were cyclically loaded. Seventeen specimens of the total 28 constructed within the overall test program were finished with wet materials following the initial Phase 1 wet specimen testing (which focused on boundary conditions); thus, they are included in the present report. Table 2.1 summarizes the variables for specimens described herein.

Table 2.1 **Test matrix for report. All specimens have wet (stucco) exterior finishes emulating detailing of the pre-1945 era.**

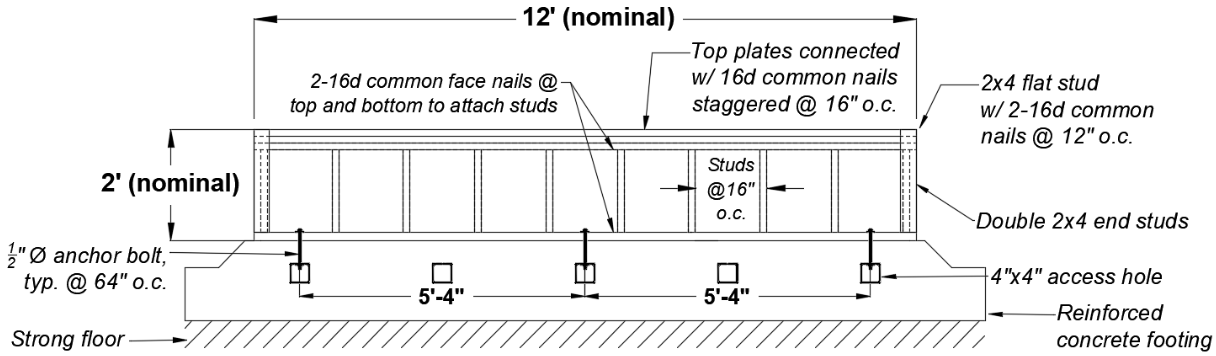
Phase	Specimen	Test no. (date)	Existing or retrofit	CW Height (ft)	Anchorage	Exterior Finish	Bottom BC	Loading	Test date
3	A-15	20	E	2	S(64 in.)	S+DSh	c	C	**11/20/2018**
	A-16	21	**R**	2	**S(32 in.)**	S+DSh	c	C	**2/5/2019**
	A-17	18	E	2	S(64 in.)	S	**d**	C	**11/5/2018**
	A-18	22	**R**	2	**S(32 in.)**	S	**d**	C	**11/13/2018**
	A-19	19	**R**	2	**S(32 in.)**	S+HSh	c	C	**10/22/2018**
	A-20	15	E	2	S(64 in.)	S+HSh	**d**	C	**10/31/2018**
	A-21	17	E	2	S(64 in.)	S+HSh	c	C	**10/26/2018**
	A-22	16	E	2	**WS**	S	c	C	**10/29/2018**
4	A-25	27	E	**6**	S(64 in.)	S	c	C	**10/29/2019**
	A-26	28	**R**	**6**	**S(32 in.)**	S	c	C	**11/7/2019**
	A-27	26	E	2	S(64 in.)	S+HSh	c	**M**	**10/25/2019**
			Retrofit	6-ft-tall	Wet Set Sill or Retrofit		Case d	Monotonic	

Notes: E = existing, R = retrofit, S = anchor bolt spacing, WS = wet set sill plate, S = stucco, HSh = horizontal sheathing, DSh = diagonal sheathing, BC = boundary condition, lowercase letters = bottom boundary condition, C = cyclic, and M = monotonic

2.2 CRIPPLE WALL DETAILS

As shown in Figure 2.1, nine of the eleven cripple wall specimens in this report are nominally 2 ft in height and 12 ft in length. The remaining two specimens are nominally 6 ft in height and 12 ft in length; see Figure 2.2. Note that the anchor bolt spacing shown in these figures applies on to existing specimen. Minor differences in length can be attributed to the nuances of the exterior finish detailing. The height of the cripple wall is measured from the base of the sill plate to the top of the uppermost top plate. Framing members were constructed with #2 Douglas Fir, with wall studs and top plates nominal 2 × 4 members and sill plates nominal 2 × 6 members except for the specimens with the wet set sill plate, which were nominal 2 × 6 members constructed with construction-grade redwood. All studs were placed at 16 in. on center and connected to the sill plate and top plate with 2-16d (0.165-in.-diameter) common nails per stud. In the case of a wet set sill plate, studs were attached to the sill plate with 3-8d (0.131-in.-diameter) common nails and toe-nailed per stud. Additional top plates were connected with 16d common nails staggered at 16 in. on center. All lumber used was tested for moisture content. Upon procurement of the lumber, the moisture content was between 10–25% for both the Douglas Fir and redwood (studs, sill plates, top plates, and sheathing boards). The moisture contents were read before testing for all lumber, with a moisture content in the range of 5–15%. The loss of moisture can be attributed to the walls drying awaiting testing. All moisture content readings are given in Appendix A.1.

The top boundary condition for all eleven cripple wall specimens was the same with two different options for the bottom boundary condition: top boundary condition B or bottom boundary condition "c" or "d", which were characterized in Phase 1. The following sections will only highlight the details pertaining to the boundary conditions adopted herein. An in-depth evaluation of all boundary conditions considered in the overall small-component testing program can be found in the first report in this series [Schiller et al. 2020(a)].



Notes:
1. Sill plates are 2x6 and top-plates are 2x4.
2. Anchor bolts are ½" Ø with 2 ½" (min.) x $\frac{3}{16}$" square washer (to receive load cell on top).

Elevation
Framing Details (Interior Face)
2' Tall Cripple Wall

Figure 2.1 2-ft-tall cripple wall framing.

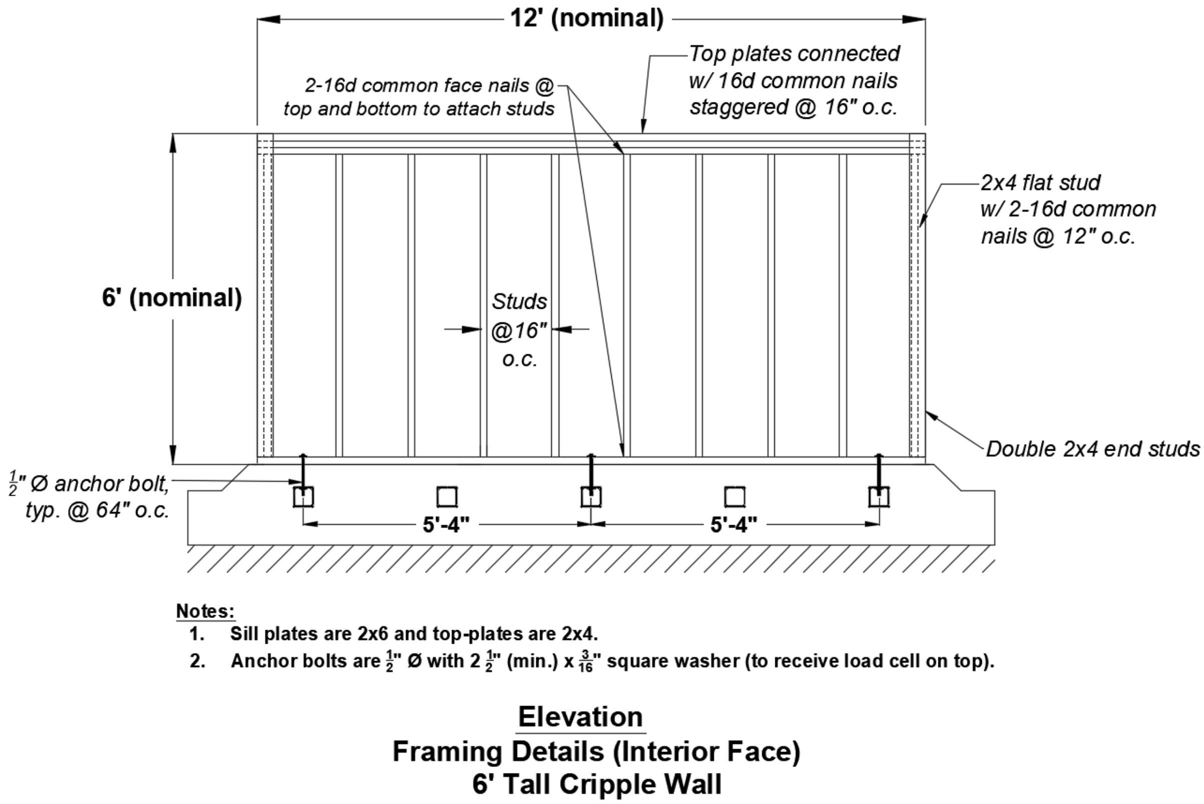


Figure 2.2 6-ft-tall cripple wall framing.

Anchor bolts used were all 1/2-in. all-thread F1554 Grade 36 straight rods, with nuts and washers at both ends. The anchor bolts were not cast in the foundation but installed in prepared through holes to allow for ease in removal of the specimen. To accommodate this, the concrete footings were cast with 4 in. × 4 in. access holes to allow for the anchor bolts to be tightened and replaced if damaged during testing. The access holes were spaced 32 in. apart to allow for the prescribed 32 in. on center and 64 in. on center of anchor bolts. The footings were cast with poured-in-place concrete, with a 28-day compressive strength target of 8 ksi. The rebar arrangement and details of the footing can be seen in Figure 2.3. Anchor bolt holes were oversized by 1/4 in., which is a common building practice in California as it facilitates ease of construction. Square washers (2 in. × 2 in. × 3/16 in.), overlaid with spherical washers were used at the anchor bolt connection at the sill plate, allowing for placement of 10-kip donut load cells used to measure the tensile force in the anchor bolts during testing. Conventional nuts and washers were used at the bottom anchor bolt connection within the 4 in. × 4 in. access hole. The load cell configuration can be seen in Figure 2.4.

The primary resistance to sliding during imposition of lateral load to the specimen comes from the frictional resistance at the interface of the sill plate and the foundation, and the bearing of the anchor bolt on the sill plate. By oversizing the anchor bolt holes, the cripple walls have less resistance to sliding. As such, it is noted that sliding of the walls was observed for certain specimens, prior to development of bearing between the anchor bolt within its hole. Because both the global lateral displacement response and the relative lateral displacement response vary, they are discussed in detail in Chapter 3. The global lateral response includes the displacement of the cripple wall and the sliding of the sill plate; the relative lateral response only considers the displacement of the actual cripple wall structure.

The retrofit design used in this testing phase were consistent with the current recommendations from the *FEMA P-1100* prescriptive retrofit guidelines. The methodology for selecting the retrofit design will be discussed in detail in Section 2.6.

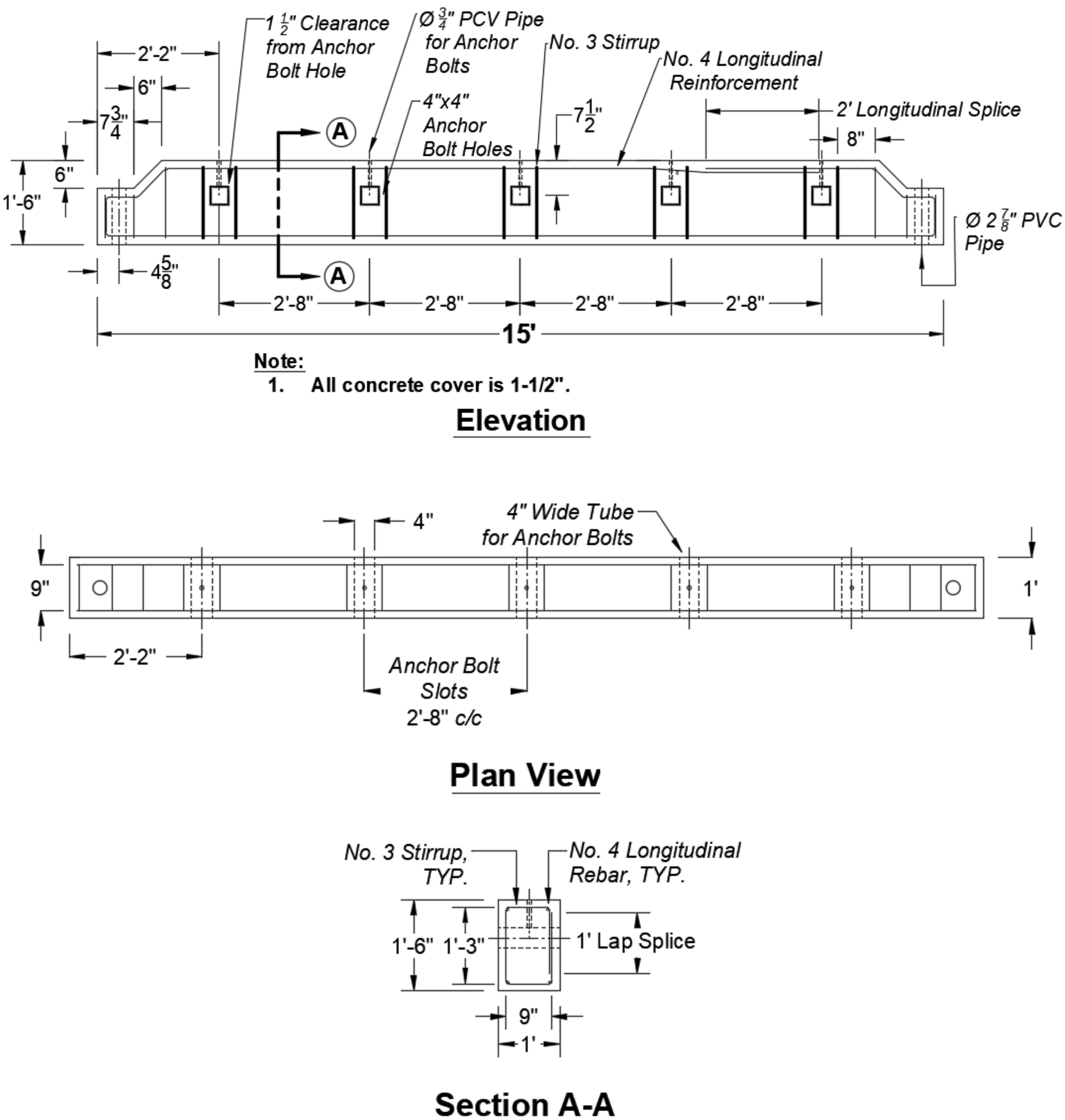


Figure 2.3 Concrete footing details for cripple wall tests.

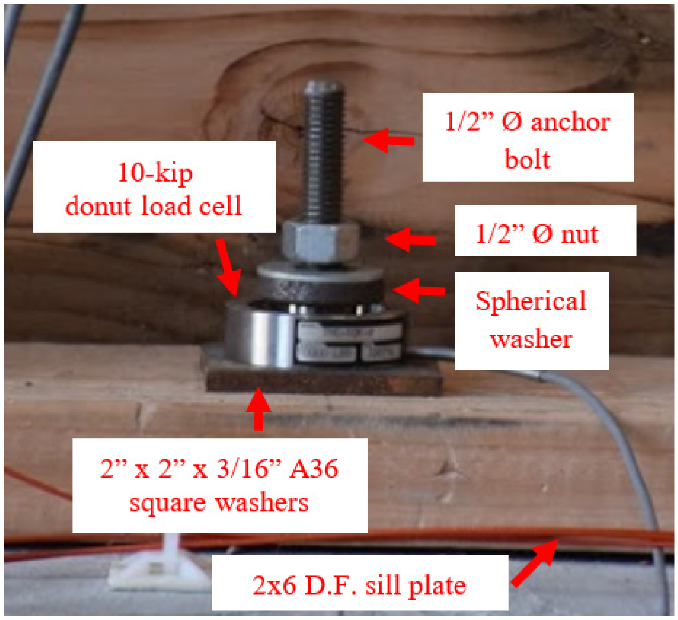


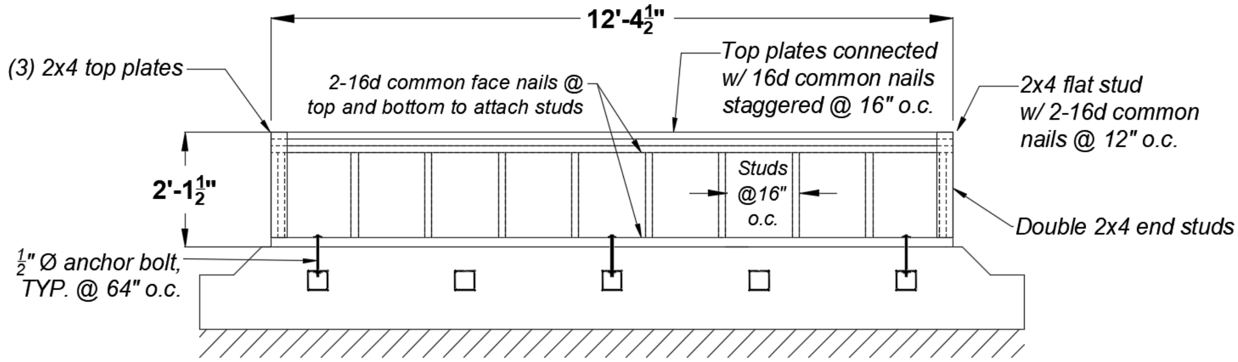
Figure 2.4 Load cell and square plate washer for anchor bolts.

2.3 BOUNDARY CONDITIONS

This testing regime split the boundary conditions into two categories, namely, top and bottom boundary conditions. Based on the results of the Phase 1 tests, all specimens herein were constructed with the same top boundary condition: top boundary condition B. Most specimens were constructed with bottom boundary condition “c”; however, an additional boundary condition (bottom boundary condition “d”) was also tested in this program. It is noted that top boundary condition B and bottom boundary condition “c” were adopted as the baseline condition for all specimens following Phase 1.

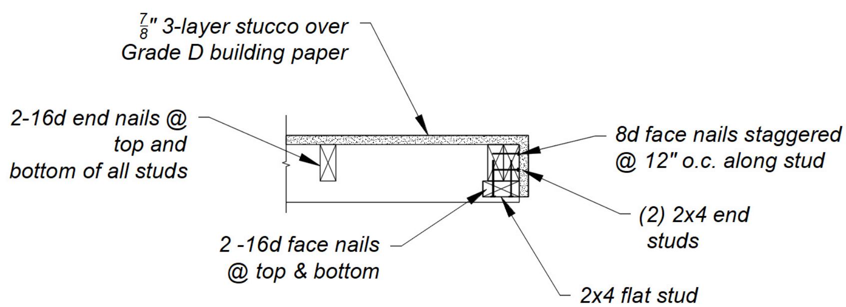
2.3.1 Top Boundary Condition B

Top boundary condition B contained built-up ends as well as an additional top plate. The built-up wall ends were typical to those seen in California houses at re-entrant corners (corners where return walls would be present). These simulated corners contained two 2 × 4 studs instead of a single 2 × 4 stud and an additional 2 × 4 flat stud abutted against the interior side of the framing. The additional top plate was originally provided to allow for a denser furring nail arrangement at the top of the cripple wall. This detail was continued for the non-stucco specimens to maintain a uniform height for all specimens with top boundary condition B. Similar to the stucco specimens, all exterior finishes were terminated at the top of the upper top plate. The framing details for top boundary condition B can be seen in Figure 2.5. The top of the wall and corner details specific to the stucco over framing specimens can be seen in Figure 2.6. Photographs of this boundary condition for the stucco only finished specimens are provided in Figure 2.7. Figures 2.8 and 2.9 provide the same details for stucco over horizontal sheathing finished cripple walls, and Figures 2.10 and 2.11 show these details for the stucco over diagonal sheathing. Nailing details for attachment of the exterior finishes are provided in Section 2.3.

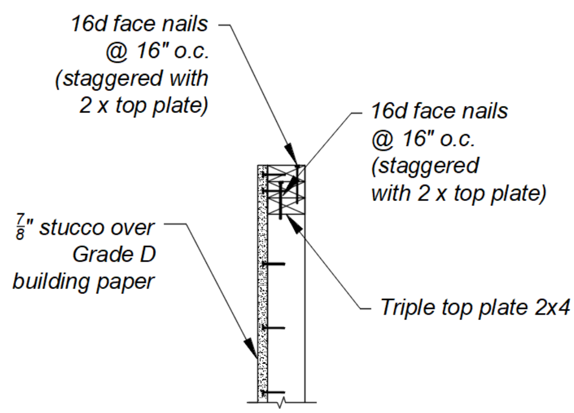


Elevation
Top Boundary Condition B

Figure 2.5 Framing detail elevation for top boundary condition B.



Plan View Detail
Stucco Only (S)
Top Boundary Condition B



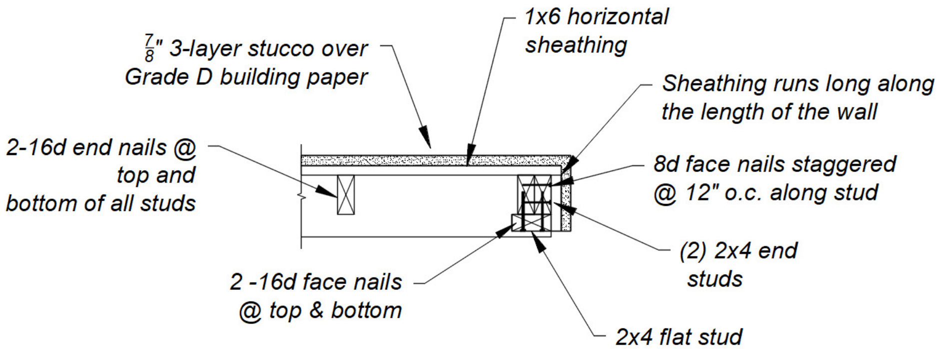
Top of Wall Detail
Stucco Only (S)
Top Boundary Condition B

Figure 2.6 Corner and top of wall detail for stucco over framing exterior finish with top boundary condition B.

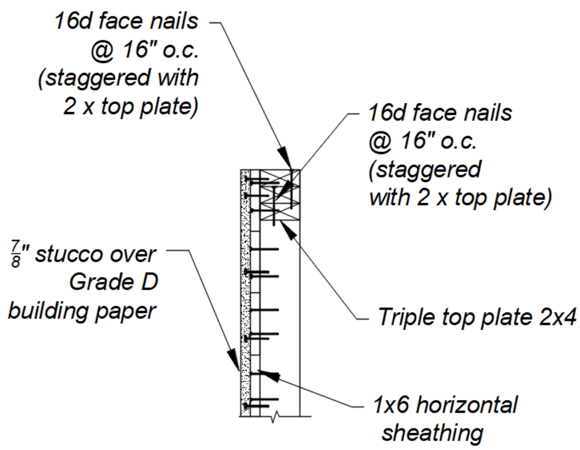
(a)

(b)

Figure 2.7 Isometric corner views showing top boundary condition B details of stucco over framing finished cripple walls: (a) south-end exterior corner; and (b) south-end interior corner.



Plan View Detail
Stucco Over Horizontal Sheathing (S+HSh)
Top Boundary Condition B

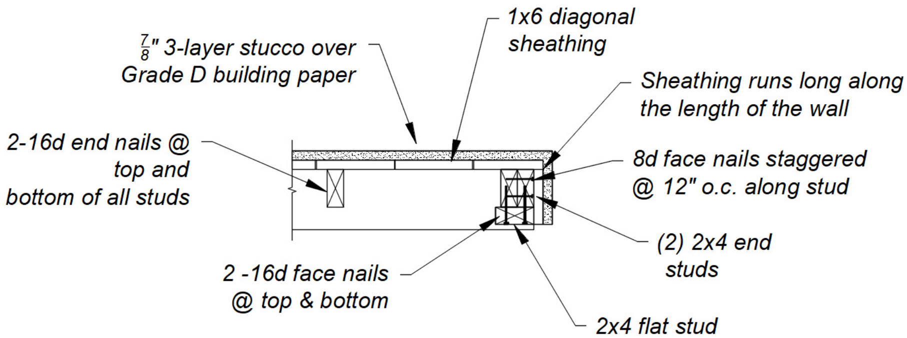


Top of Wall Detail
Stucco Over Horizontal Sheathing (S+HSh)
Top Boundary Condition B

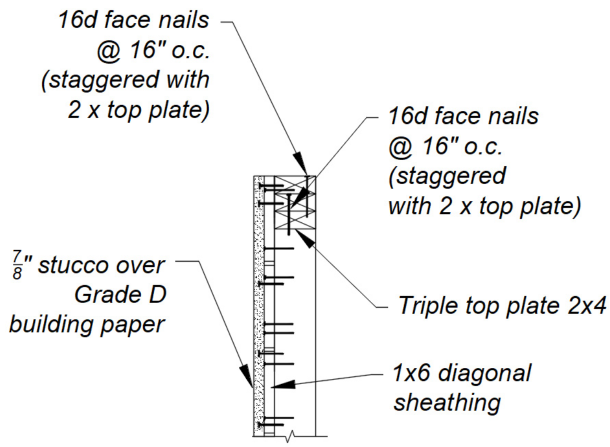
Figure 2.8 **Corner and top of wall detail for stucco over horizontal sheathing exterior finish with top boundary condition B.**

(a) (b)

Figure 2.9 **Isometric corner views showing top boundary condition B details of stucco over horizontal sheathing finished cripple walls: (a) south-end exterior corner; and (b) south-end interior corner.**



Plan View Detail
Stucco Over Diagonal Sheathing (S+DSh)
Top Boundary Condition B



Top of Wall Detail
Stucco Over Diagonal Sheathing (S+DSh)
Top Boundary Condition B

Figure 2.10 Corner and top of wall detail for stucco over diagonal sheathing exterior finish with top boundary condition B.

(a) (b)

Figure 2.11 Isometric corner views showing top boundary condition B details of stucco over diagonal sheathing finished walls: (a) south-end exterior corner; and (b) north-end interior corner.

2.3.2 Bottom Boundary Condition "c"

Bottom boundary condition "c" oriented the cripple wall so that all exterior finishes were outboard of foundation. This is the same whether there was a combined finish material or whether there was only the presence of a siding or stucco finish. Regardless of a single or combined finish material, the first layer of material attached to the framing was flush with the face of the footing. It is a common condition in California homes to have the stucco extending down the face of the footing to the ground. In older homes, however, this stucco has often deteriorated, with little bond left between the stucco and the foundation.

Bottom boundary condition "c" emulates the condition where there is no bond between the stucco and foundation by having the stucco terminate at the top of the foundation. In practice, there was a small length of stucco that extended beneath the top of the foundation that was utilized in the construction of this phase of wet specimen construction. This minor variation was elected for use by the contractor in this second wet phase of stucco finished specimens and is notably different from the first phase of stucco finished walls [Schiller et al. 2020(a)]. The contractor for the specimens described herein elected to terminate the stucco by tapering it off at the bottom of the sill plate, which created around a 1-in. lip of stucco below the sill plate, as shown in Figure 2.16. Specimens A-15 through A-22 were constructed in this manner.

For the last phase of wet construction specimens discussed herein, a different contractor was selected due to limited availability of the contractor utilized in the first phase of wet specimen construction. The research team allowed some flexibility in construction; the contractor in the present phase suggested use of a metal form to hold the stucco in place, as shown in Figure 2.15(d). Therefore, the stucco was extended slightly more than those of Specimens A-15 and A-22, with about 2 in. of extension along the footing. It is noted that this extension was backed with building paper, so there was no bond between the stucco and the footing. Specimens A-25, A-26, and A-27 were constructed in this manner.

Bottom boundary condition “c” allowed all finish materials to rotate freely as the cripple wall deformed. It is noted that this condition was tested in both a typical sill on foundation and a wet set sill configuration. The bottom of the wall details specific to the stucco over framing specimens can be seen in Figure 2.12. Photographs of this boundary condition for the stucco only finished specimens are provided in Figure 2.13. Figures 2.14 and 2.15 provide the same details for stucco over horizontal sheathing finished cripple walls. Photographs of bottom boundary condition “b” for a specimen with a wet set sill plate are shown in Figure 2.16. Figures 2.17 and 2.18 show these details for the stucco over diagonal sheathing. Nailing details for attachment of the exterior finishes are provided in Section 2.3.

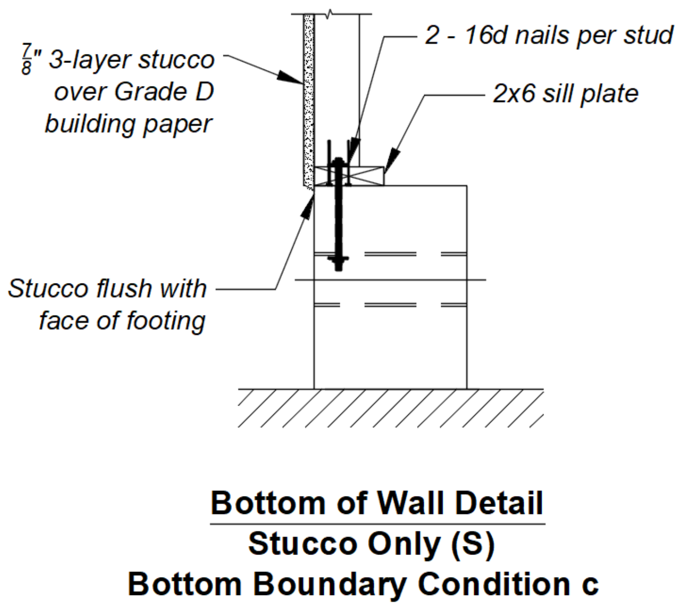
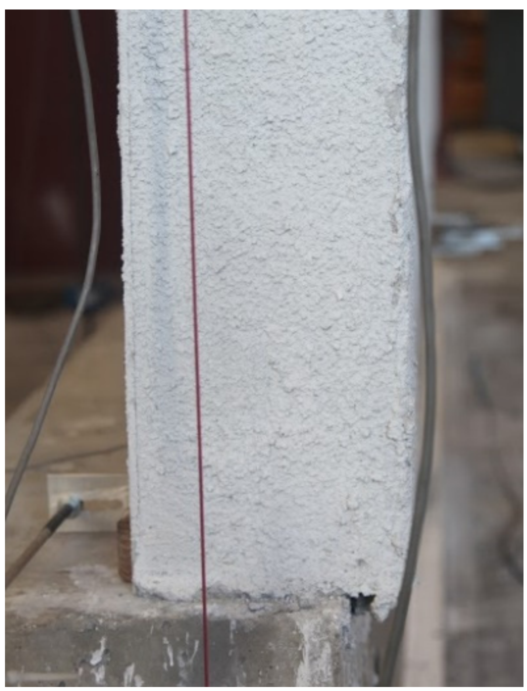


Figure 2.12 **Bottom of the wall detail for stucco over framing exterior finish with bottom boundary condition “c”.**

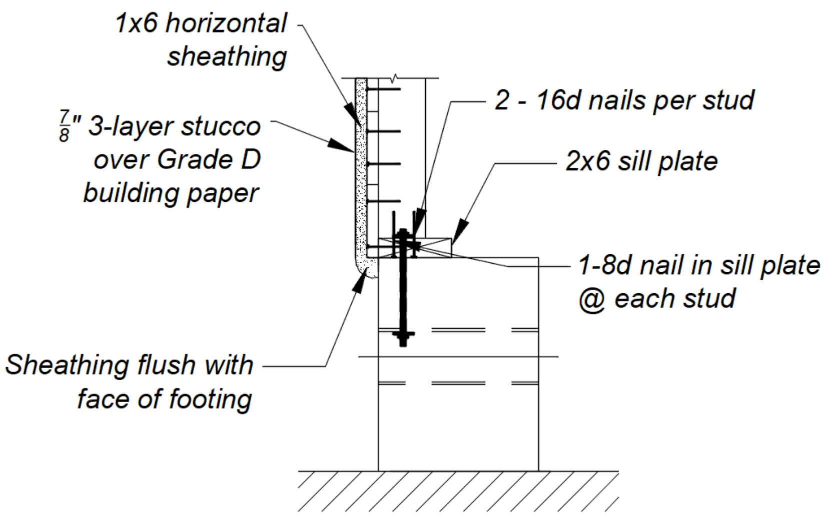
(a)

(b)

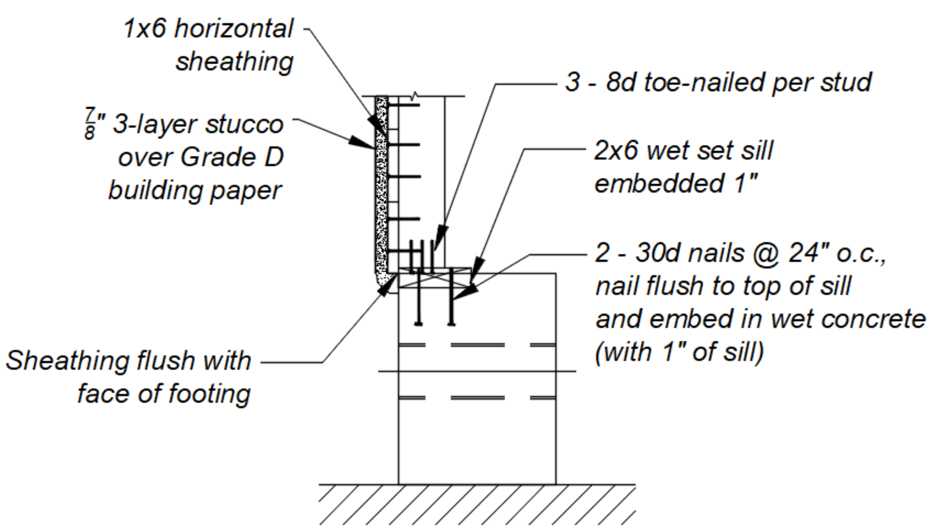


(c)

Figure 2.13 Corner views showing bottom boundary condition "c" details of stucco over framing finished cripple walls: (a) north-end exterior corner; (b) south-end interior corner; and (c) bottom of south-end corner.



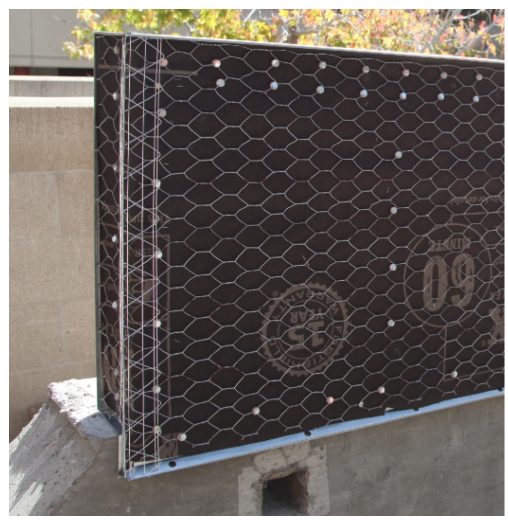
Bottom of Wall Detail
Stucco Over Horizontal Sheathing (S+HSh)
Bottom Boundary Condition c



Bottom of Wall Detail
Stucco Over Horizontal Sheathing (S+HSh)
Wet Set Sill Plate
Bottom Boundary Condition c

Figure 2.14 **Bottom of the wall detail for stucco over horizontal sheathing exterior finish with bottom boundary condition “c”, a typical sill plate on top and a wet set sill plate on bottom.**

(a) (b)



(c) (d)

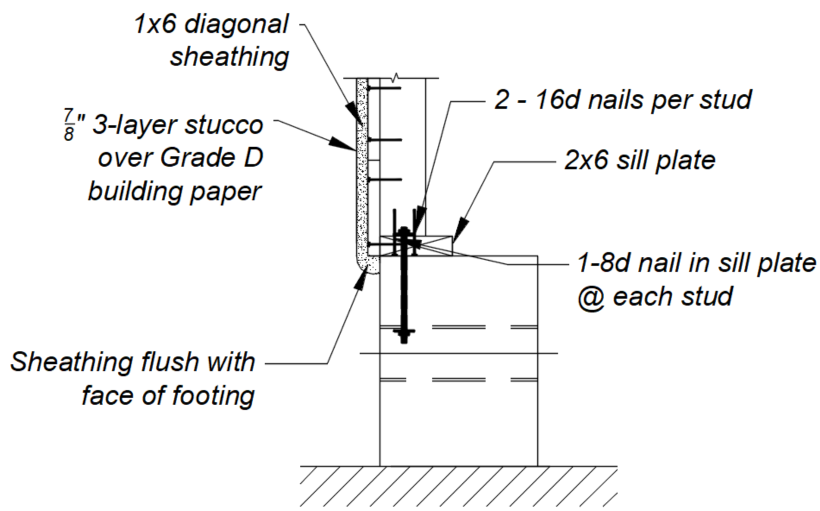
Figure 2.15 Corner views showing bottom boundary condition "c" details of stucco over horizontal sheathing finished cripple walls: (a) south-end exterior corner; (b) south-end interior corner; (c) bottom of north-end corner; and (d) corner of wall before stucco application.

(a)

(b)

(c)

Figure 2.16 Corner views showing bottom boundary condition "c" details of stucco over horizontal sheathing finished cripple walls with a *w*et set sill plate: (a) south-end exterior corner; (b) south-end interior corner; and (c) bottom of south-end corner.



Bottom of Wall Detail
Stucco Over Diagonal Sheathing (S+DSh)
Bottom Boundary Condition c

Figure 2.17 **Bottom of the wall detail for stucco over diagonal sheathing exterior finish with bottom boundary condition “c”.**

(a)

(b)

(c)

Figure 2.18 Corner views showing bottom boundary condition “c” details of stucco over horizontal sheathing finished cripple walls: (a) south-end exterior corner; (b) north-end interior corner; and (c) bottom of north-end corner.

2.3.3 Bottom Boundary Condition "d"

Bottom boundary condition "d" pertained to cripple walls with stucco only or stucco over sheathing exterior finish. This boundary condition was similar to boundary condition c; however, the stucco was extended down the face of the footing. This also is a very common condition found in California houses, particularly in cases where the foundation stem wall is extended above grade. In this scenario, home builders would often extend the stucco to meet the soil or hardscape grade rather than terminate it at the base of the sill plate. As seen in Figure 2.20, the tail extension of the stucco ran 8 in. down the face of the foundation. This inevitably created a thicker patch of stucco when sheathing was present in the finish, as it is also outboard of the foundation. The bottom of the wall details specific to the stucco over framing specimens can be seen in Figure 2.19. Photographs of this boundary condition for the stucco-only finished specimens are provided in Figure 2.20. Figures 2.21 and 2.22 provide the same details for stucco over horizontal sheathing finished cripple walls.

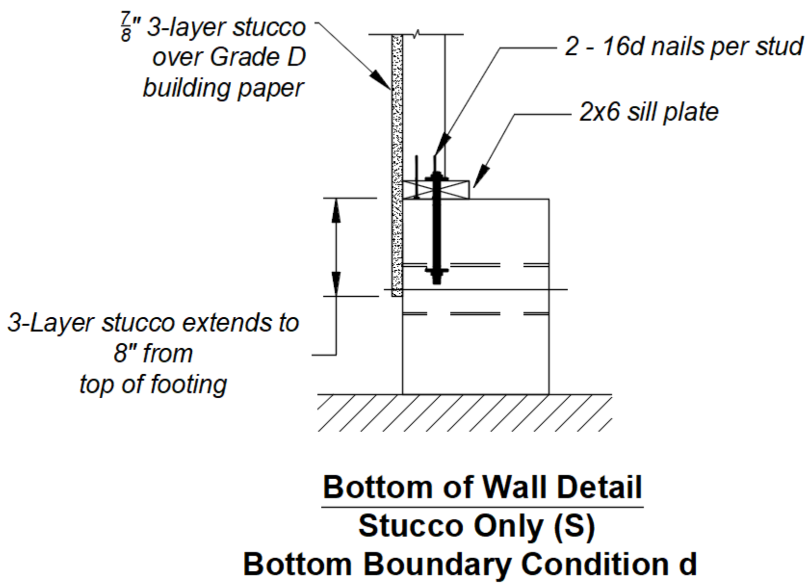


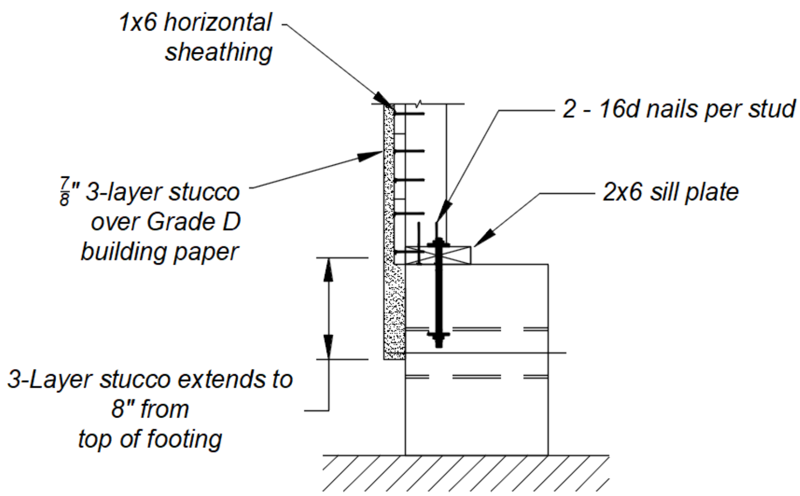
Figure 2.19 Bottom of the wall detail for stucco over framing exterior finish with bottom boundary condition "d".

(a)

(b)

(c)

Figure 2.20 Corner views showing bottom boundary condition "d" details of stucco over horizontal sheathing finished cripple walls: (a) south-end exterior corner; (b) south-end interior corner; and (c) bottom of south-end corner.



Bottom of Wall Detail
Stucco Over Horizontal Sheathing (S+HSh)
Bottom Boundary Condition d

Figure 2.21 **Bottom of the wall detail for stucco over horizontal sheathing exterior finish with bottom boundary condition "d".**

(a) (b)

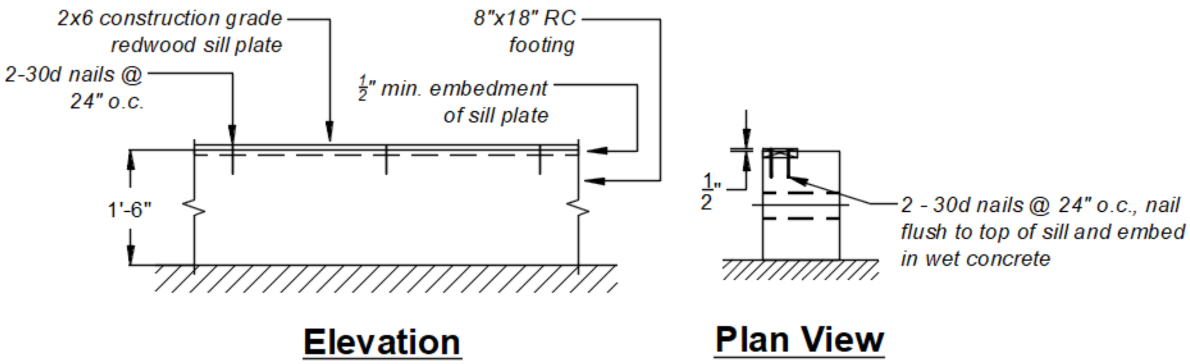
(c)

Figure 2.22 Corner views showing bottom boundary condition “d” details of stucco over horizontal sheathing finished cripple walls: (a) south-end exterior corner; (b) south-end interior corner; and (c) bottom of south-end corner.

2.4 WET SET SILL PLATE

Although not as common as a traditional sill plate placed atop a foundation and tied down with anchor bolts, wet set sill plates have a statistically significant presence in California homes, especially in older construction. In addition, no information is available on the performance of wet set sill plates. Traditionally, wet set sill plates are 2 × 4 or 2 × 6 wood sill plates that are placed or set-in foundations when the concrete is being poured, as shown in Figure 2.23. The sill is usually prepared prior to the pour with a series of nails that may provide additional load transfer. In these tests, the wet set sill used was a construction grade redwood 2 × 6 with 2-30d nails driven through the sill at 24 in. center-to-center spacing along the board length. The nailed side was set in the wet foundation to provide additional resistance to movement of the sill plate. Details of the wet set sill and the construction procedure can be seen in Figure 2.24. A view of the wet set sill plate used in Specimen A-21 can be seen in Figure 2.25.

Figure 2.23 Specimen A-21 sill plate being wet set into the footing.



Notes:

1. Set form w/ plywood or 1x8 sheathing material to 19" tall by 12" wide.
2. 2x6 Construction Grade Redwood wet set sills are cut to desired length.
3. Trowel in wet concrete to fit the form.
4. Check the level on top and width of form.
5. Place a center line in the wet concrete to form alignment for wet set sill.
6. Embed the protruding nails into the concrete so that the sill is embedded 1".
7. Check level of sill and use flat head hammer to make adjustments.
8. Add additional bracing/blocking as needed to keep form while curing.
9. Chisel away excess concrete as need be.

Figure 2.24 Wet set sill plate view and construction procedure.

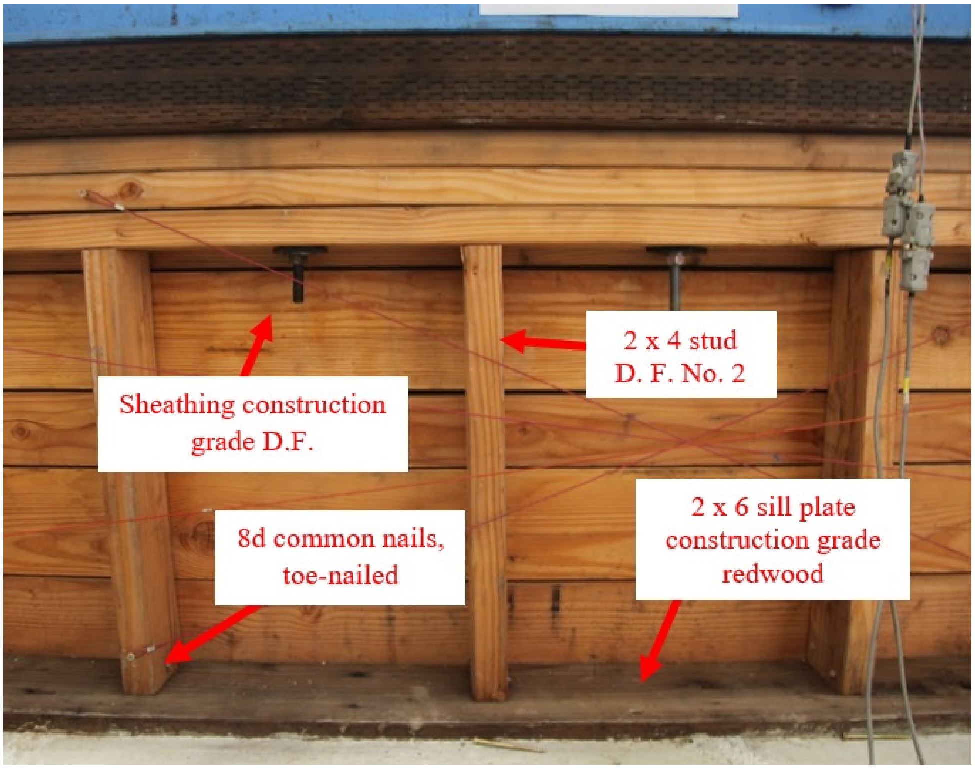


Figure 2.25 Specimen A-21 wet set sill plate.

2.5 INSTALLATION OF FINISHES

The eleven cripple walls discussed in this report were constructed with three different wet exterior finishes, namely: stucco over framing (5), stucco over horizontal lumber sheathing (4), and stucco over diagonal lumber sheathing (2). Of the five cripple walls constructed with stucco over framing, three of the specimens were 2 ft tall and two of the specimens were 6 ft tall. All other specimens were 2 ft tall.

Figure 2.26 provides an elevation view of details for a 2-ft-tall cripple wall with a stucco over framing exterior finish with bottom boundary condition “c”. Figure 2.27 is a photograph of Specimen A-22, a cripple wall with these conditions. Figure 2.28 provides details for both stucco over framing and stucco over horizontal sheathing finished cripple walls with bottom boundary condition “d”. Since the layout of the stucco is the same for both finishes, the two finishes are combined in Figure 2.28. A photograph of the exterior elevation for a stucco over framing finished cripple wall with bottom boundary condition “d” is provided in Figure 2.29. Elevation details and photographs of Specimen A-25, a 6-ft-tall cripple wall with stucco over framing exterior finish, are shown in Figures 2.30 and 2.31, respectively. The nailing details for stucco over framing exterior finishes are provided in Figure 2.32, which includes a top of the wall view, bottom of the wall view, and plan view. Figure 2.33 shows an elevation view of details for a stucco over horizontal sheathing finished cripple wall. Exterior and interior elevation photographs for this finish style can be seen in Figure 2.34. The same nailing details as with the stucco over framing finish are given in Figure 2.35. Figures 2.36 through 2.38 provide the elevation view of details, elevation photographs, and nailing details for cripple walls with stucco over diagonal sheathing exterior finishes.

For consistency, the same details, material, and contractor were used for the application of the stucco, and the same details and materials were used for the application of the sheathing. Sheathing boards used were 1 × 6 nominal (7/8-in. × 5-1/2-in.) construction-grade Douglas Fir. For horizontal sheathing, full boards were placed at the top and bottom of each wall. An 1/8-in. gap was placed between each board to allow for expansion. The middle sheathing board was cut to match the required dimension to fit in the middle of the wall, as shown in Figure 2.39. With the exception of the middle board, all sheathing boards were attached with 2-8d common hot-dipped galvanized nails per stud. The middle board was attached with 1-8d common hot-dipped galvanized nail per stud. Diagonal sheathing boards were installed at a 45° angle. An 1/8-in. gap was placed between each board to allow for expansion.

Installation for the diagonal sheathing started with a full width board at one end, and each board after that was cut to fit onto the framing of the cripple wall, as shown in Figure 2.40. Boards along the front face of the cripple walls extended 3/4 in. beyond the outer stud to allow for the boards at the corners to abut to them. An example of this can be seen Figure 2.41, showing framing with diagonal sheathing attached. The ends of each wall contained two studs, and the sheathing boards were nailed to the outermost stud only. Nails were spaced at 2-3/4 in. apart on each horizontal sheathing board and 5 in. apart on each diagonal sheathing board. The spacing of the nails was increased for diagonal sheathing boards due to the increased width of each board along the studs (5.5 in. for horizontal siding boards and 7-3/4 -in. for diagonal sheathing boards). Along the corner returns, each diagonal or horizontal sheathing was fastened with two 8d common, hot-dipped galvanized nails, as shown in Figure 2.41.

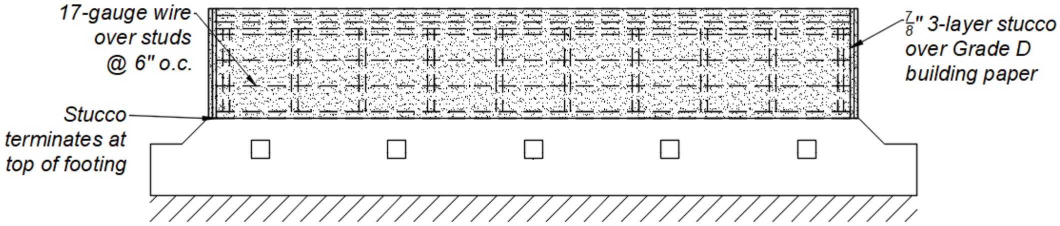


Figure 2.26 Elevation view with details for 2-ft-tall cripple wall with stucco over framing finish and bottom boundary condition "c".

(a)

(b)

Figure 2.27 Elevation view of 2-ft-tall cripple wall with stucco over framing finish with bottom boundary condition "c": (a) exterior elevation; and (b) interior elevation.

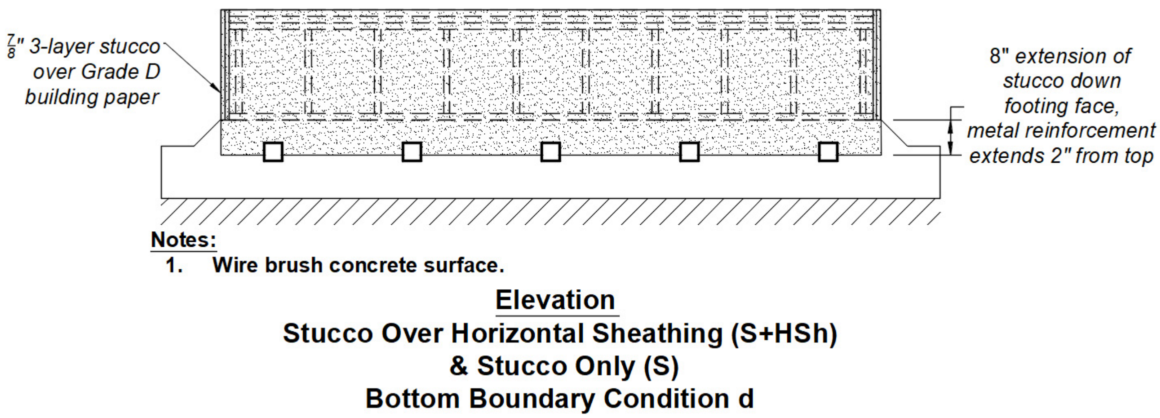


Figure 2.28 Elevation view with details for stucco over framing or stucco over horizontal sheathing finish cripple wall with bottom boundary condition "d".

Figure 2.29 Elevation view of stucco over framing or stucco over horizontal sheathing finished cripple wall with bottom boundary condition "d".

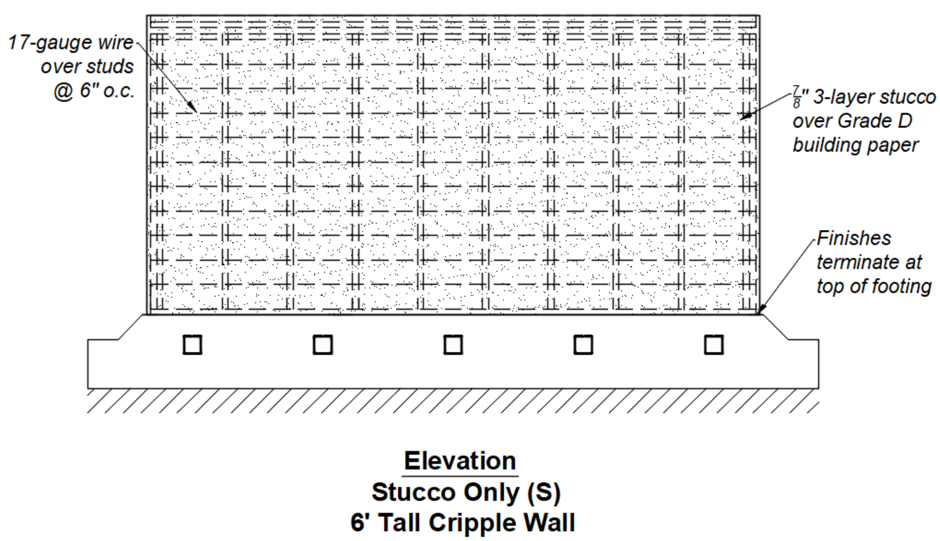
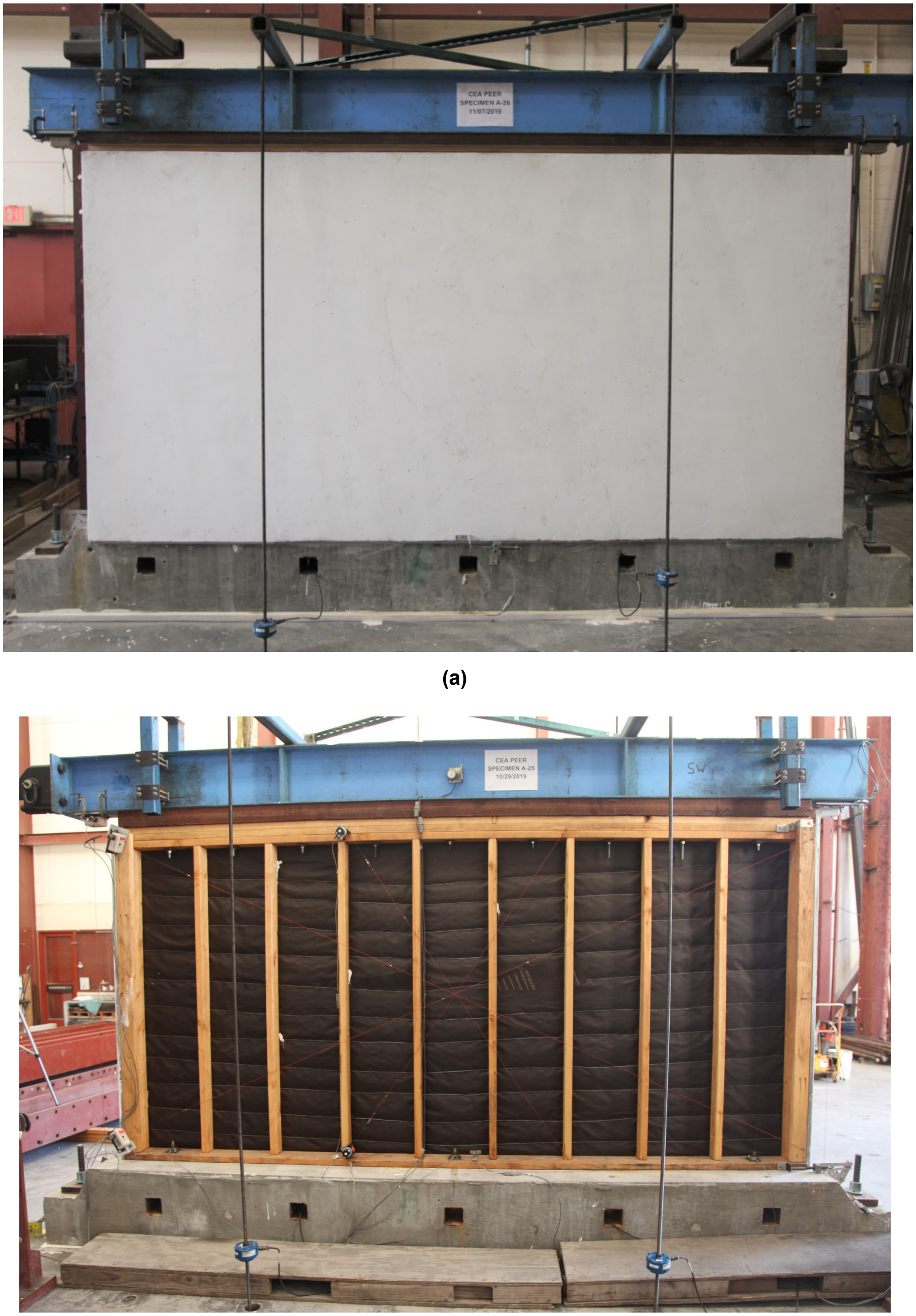


Figure 2.30 Elevation view with details for 6-ft-tall cripple wall with stucco over framing finish.



(a)

(b)

Figure 2.31 Photographs of 6-ft-tall cripple wall with stucco over framing finish: (a) exterior elevation; and (b) interior elevation.

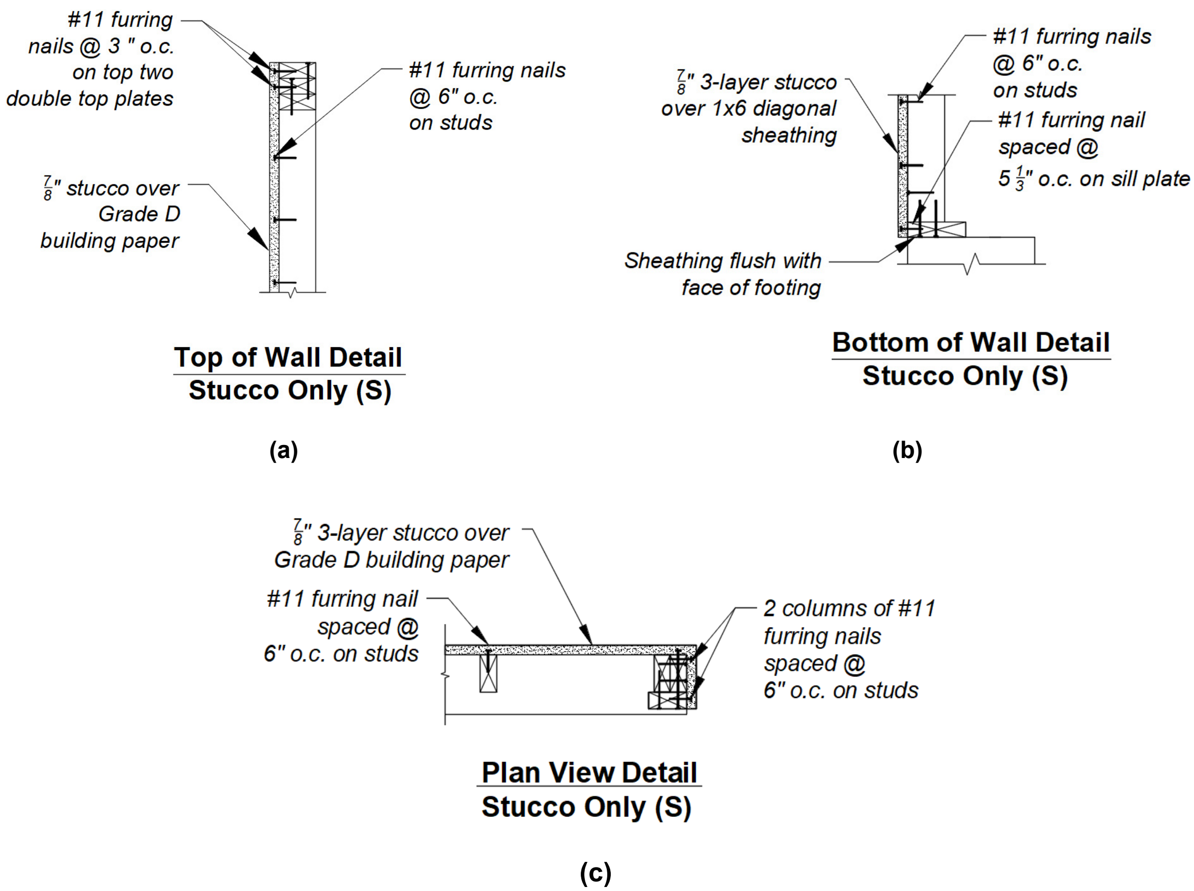


Figure 2.32 Finish nailing details for stucco over framing finished cripple walls: (a) top of cripple wall detail; (b) bottom of cripple wall detail; and (c) plan view of corner detail.

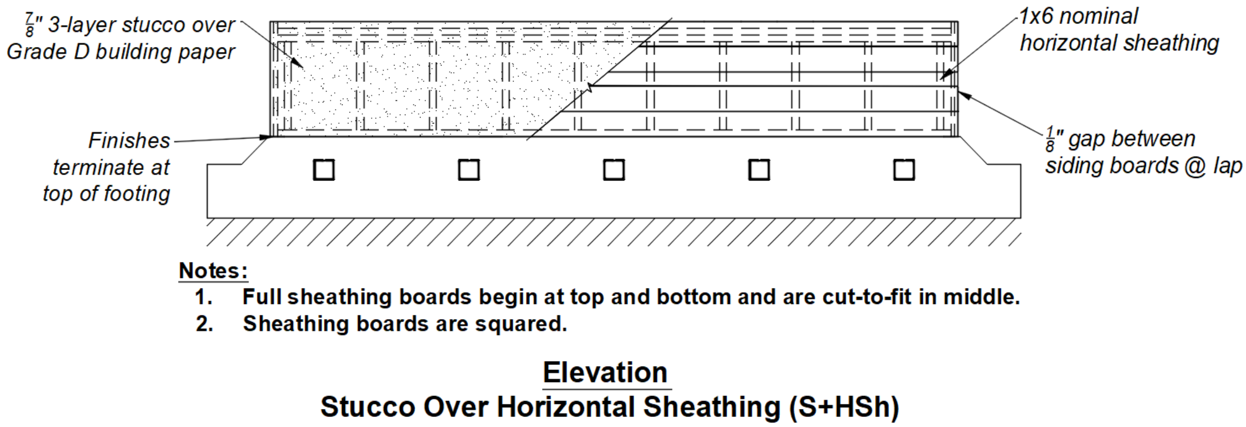
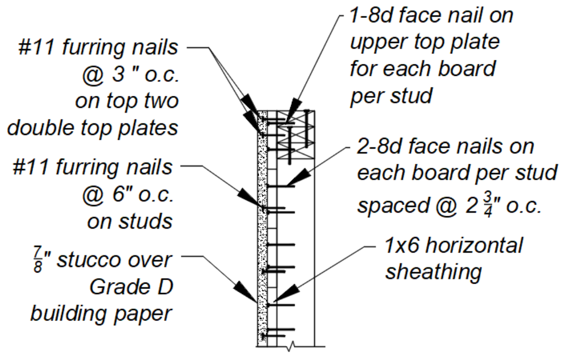


Figure 2.33 Elevation view with details for stucco over horizontal sheathing finished cripple wall.

(a)

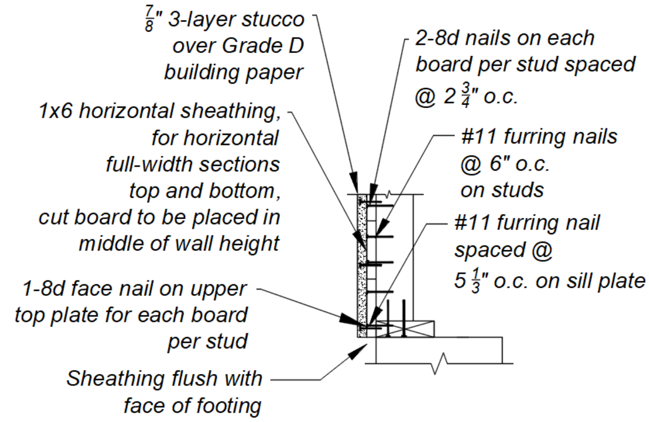
(b)

Figure 2.34 Photographs of a stucco over horizontal sheathing exterior finished cripple wall: (a) exterior elevation; and (b) interior elevation.



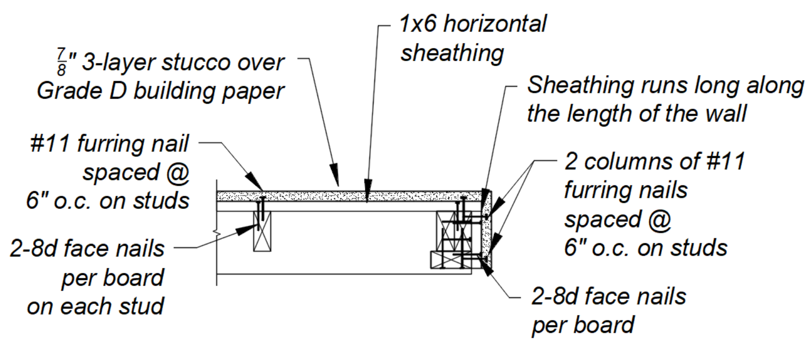
Top of Wall Detail
Stucco Over Horizontal Sheathing (S+HSh)

(a)



Bottom of Wall Detail
Stucco Over Horizontal Sheathing (S+HSh)

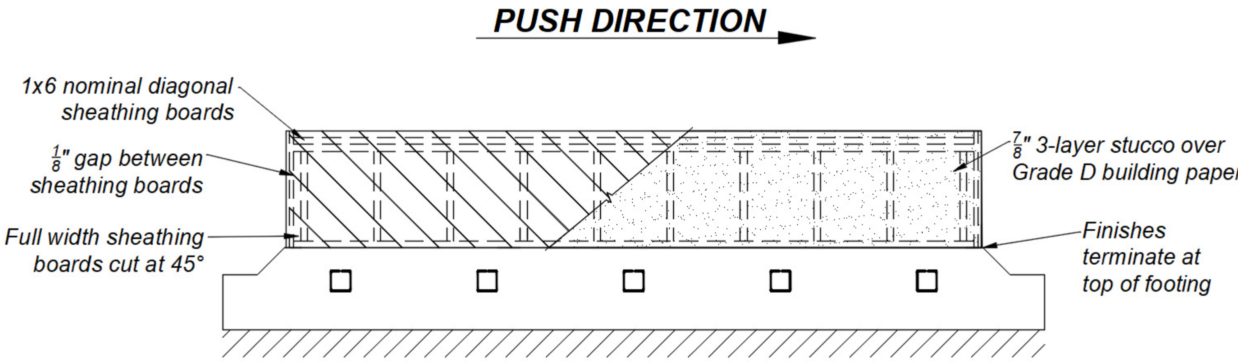
(b)



Plan View Detail
Stucco Over Horizontal Sheathing (S+HSh)

(c)

Figure 2.35 **Finish nailing details for stucco over horizontal sheathing finished cripple walls: (a) top of cripple wall detail; (b) bottom of cripple wall detail; and (c) plan view of corner detail.**



Notes:
1. **Full sheathing boards begin at South end and are cut-to-fit moving North.**
2. **Sheathing boards are squared.**

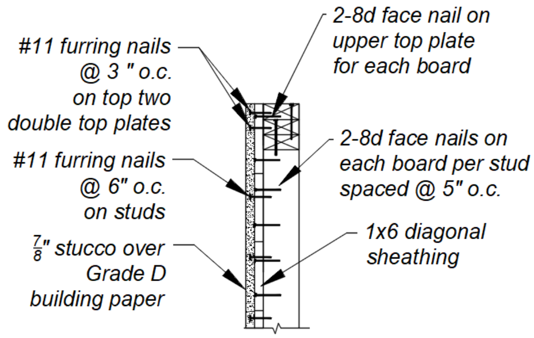
Elevation
Stucco Over Diagonal Sheathing (S+DSh)

Figure 2.36 Elevation view with details for stucco over diagonal sheathing finished cripple wall.

(a)

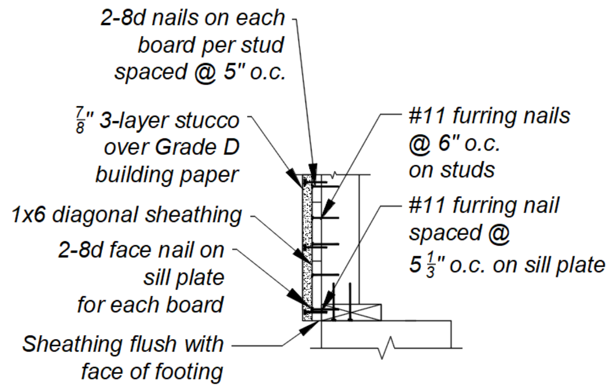
(b)

Figure 2.37 Photographs of a stucco over diagonal sheathing exterior finished cripple wall: (a) exterior elevation; and (b) interior elevation.



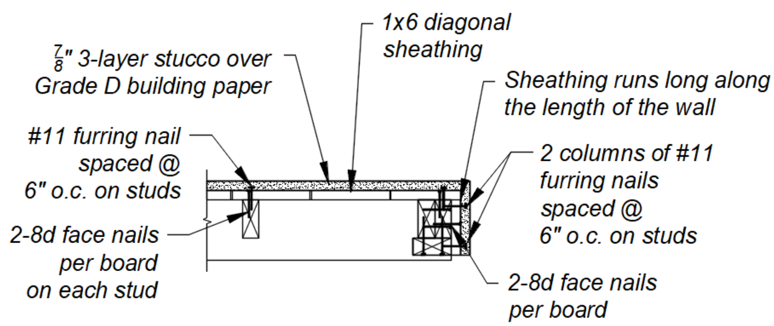
Top of Wall Detail
Stucco Over Diagonal Sheathing (S+DSh)

(a)



Bottom of Wall Detail
Stucco Over Diagonal Sheathing (S+DSh)

(b)



Plan View Detail
Stucco Over Diagonal Sheathing (S+DSh)

(c)

Figure 2.38 Finish nailing details for stucco over diagonal sheathing finished cripple walls: (a) top of cripple wall detail; (b) bottom of cripple wall detail; and (c) plan view of corner detail.

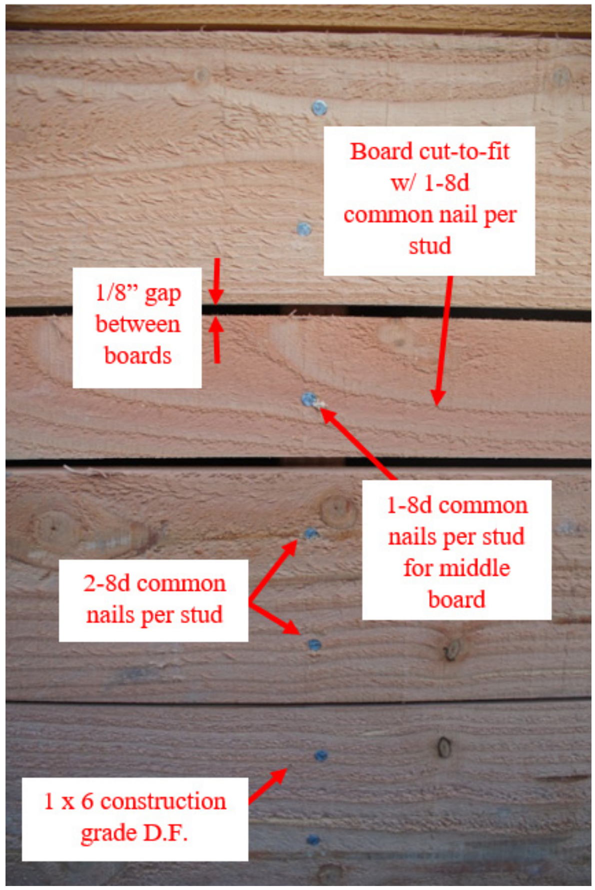


Figure 2.39 Horizontal sheathing board installation detail.

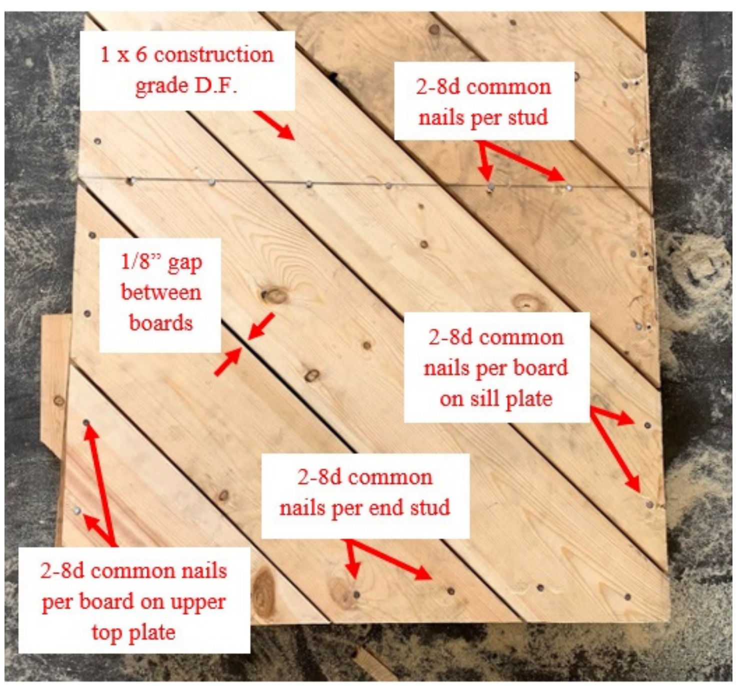


Figure 2.40 Diagonal sheathing board installation detail.

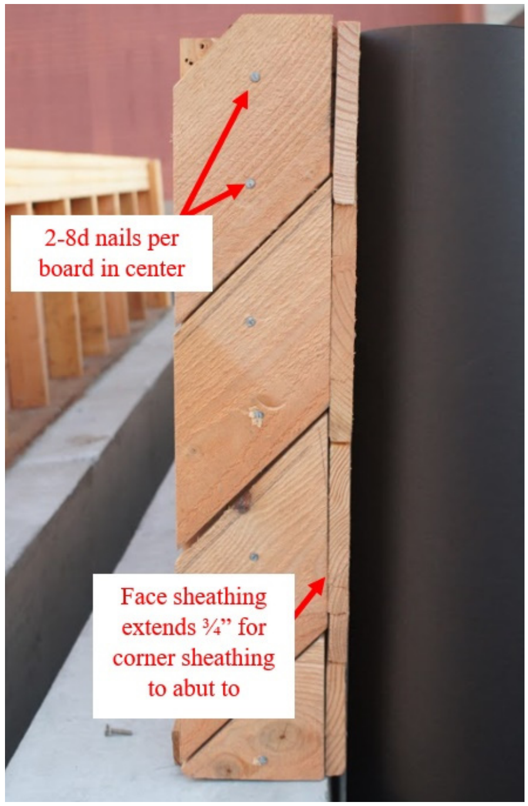


Figure 2.41 Corner detail of diagonal sheathing attachment.

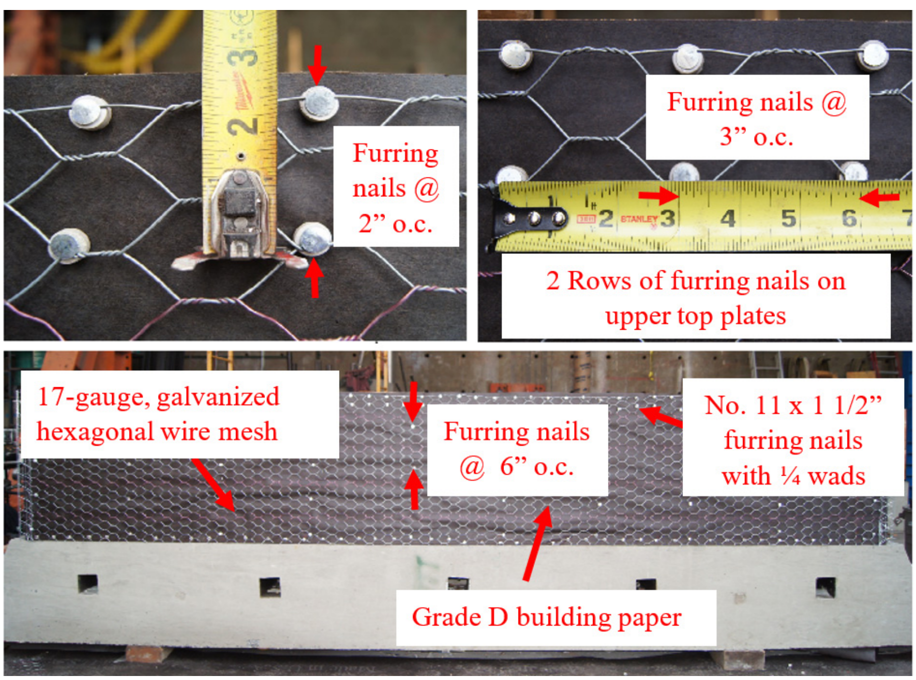
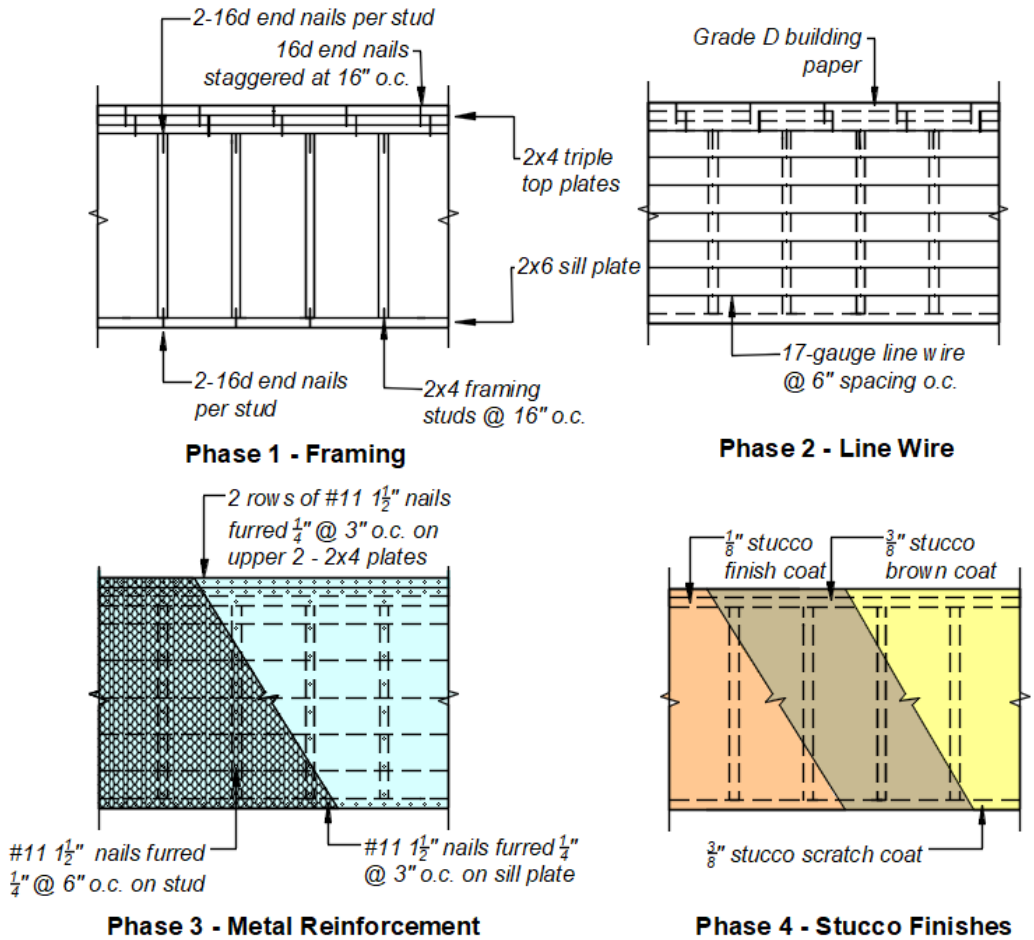


Figure 2.42 Cripple wall with metal reinforcement and furring nails attached over building paper.

To emulate the increased strength and stiffness a cripple wall would have due to the continuity of the stucco running from the cripple wall beyond the floor diaphragm, an additional top plate was added to the cripple walls to allow for an additional row of furring nails to be attached. Typically, houses are constructed with a double top plate; therefore, the specimens discussed in this report have a triple top plate. These details were previously discussed in the sections describing the top boundary condition. The furring nail arrangement can be seen in Figure 2.42. The furring nails used were #11 × 1-1/2 in. (0.121 in. diameter) nails with 1/4-in. wads to allow for proper separation between the metal reinforcement and the sheathing boards. This conforms with the 1946 UBC, which indicates that nails should be no less than 4d nails (1-1/2 in. × 0.109 in. diameter), furred 1/4 in.., with a vertical spacing of 6 in. on center [ICBO 1946].

The metal reinforcement used was a 17-gauge, galvanized, hexagonal wire mesh. This metal reinforcement meets the requirements of the 1946 UBC, which states that metal reinforcement shall be galvanized and not be thinner than 18-gauge wire as well as have openings no less than 3/4 in. and no greater than 2 in. [ICBO 1946]. A single layer of Grade D building paper was fastened to the sheathed walls using 3/8-in. staples along the studs, top plate, and sill plate. Building paper acts as a moisture barrier between the stucco finish and the horizontal sheathing.

The stucco used for the exterior finish consisted of three layers of stucco, which is typical of pre-1945 construction. The total thickness of the stucco was 7/8 in., with a 3/8-in-thick scratch coat, a 3/8-in.-thick brown coat, and a 1/8-in.-thick finish coat. The mix design used for each coat was derived from the UBC [1943] and recommendations from the Portland Cement Association stucco guidebook [Portland Cement Association 1941]. The scratch coat and brown coat both consisted of one-part Type I Portland cement to three-parts fine aggregate and 1/5-part hydrated lime. The fine aggregate was a plastering sand, which was well graded and clean with 70–90% passing through a No. 8 sieve. The hydrated lime met the ASTM C207-06 standard [ASTM 2006]. The finish coat consisted of one-part Type I Portland cement to three-parts fine aggregate, and 3/5-part hydrated lime. Clean water was added to each mixture until the plaster became workable. The amount of water required was largely left at the discretion of the stucco contractor, who targeted a workable mix; the in-place water/cement ratio ranged from 0.5 to 0.55.

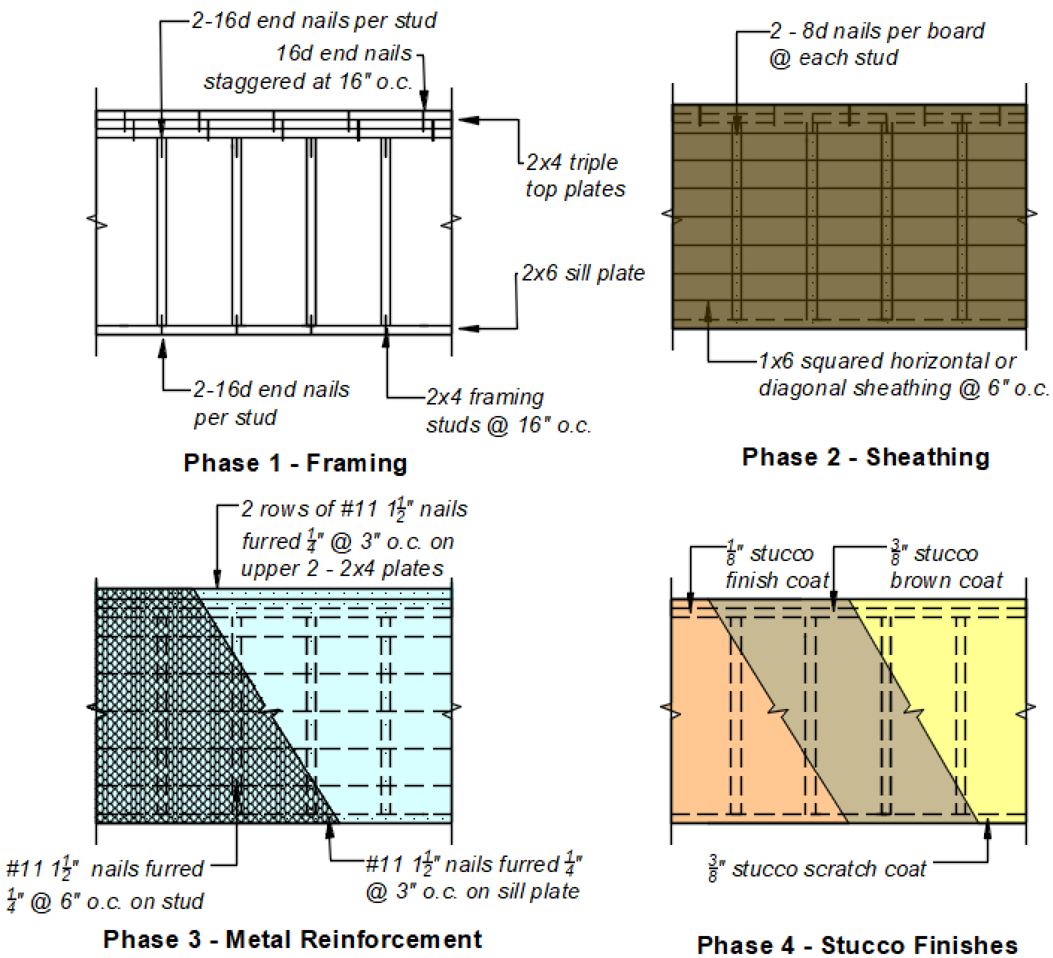


Notes:

1. Grade D building paper w/ horizontal joints lapped 2" and vertical joints lapped 6" placed directly over studs, fastened w/ $\frac{3}{8}$" staples.
2. Stucco mixtures remain consistent for scratch and brown coat.
3. Scratch coat applied first and cured 2 days while keeping moist.
4. Brown coat applied second and cured 7 days while keeping moist.
5. Finish coat applied last and cured for 3 days while keeping moist.

Elevation
Stucco Over Framing
Construction Sequence

Figure 2.43 Construction sequence of stucco over framing.



Notes:

1. Grade D building paper w/ horizontal joints lapped 2" and vertical joints lapped 6" placed directly over studs, fastened w/ 3/8" staples.
2. Sheathing is squared with no overlap, leaving a 1/8" gap between panels.
3. Full size panels start from top and bottom, the cut to width required panel should be placed at the center of each specimen.
4. Stucco mixtures remain consistent for scratch and brown coat.
5. Scratch coat applied first and cured 2 days while keeping moist.
6. Brown coat applied second and cured 7 days while keeping moist.
7. Finish coat applied last and cured for 3 days while keeping moist.

Elevation
Stucco Over Sheathing
Construction Sequence

Figure 2.44 Construction sequence of stucco over horizontal sheathing.

The construction sequence for application of the stucco over framing is provided in Figure 2.43 and for stucco over sheathing is provided in Figure 2.44. Photographs of the process are shown in Figure 2.45. The process was as follows: Following installation of the sheathing material overlaid by building paper or line wire overlaid by building paper, a 3/8-in.-thick stucco scratch coat was applied onto the building paper and metal reinforcement. Once the scratch coat was applied, the walls were covered and kept moist for 48 hours. After 4 days, a 3/8-in.-thick brown coat was applied. The walls with the brown coat were covered and kept moist for 72 hours. The brown coat was given 7 days to cure before the finish coat was applied. The 1/8-in.-thick finish coat was smooth troweled, and the walls were covered and kept moist for 3 more days to allow for the finish coat to cure. Small (2 in. × 4 in.) cylinders were used to take samples of each coat of stucco. For Phase 3 of construction, the average compressive strength was 2650 psi for the scratch coat (38 days after installation), 2900 psi for the brown coat (34 days after installation), and 790 psi for the finish coat (28 days after installation). For Phase 4 of construction, the average compressive strength was 2650 psi for the scratch coat (38 days after installation), 2070 psi for the brown coat (33 days after installation), and 1620 psi for the finish coat (26 days after installation). These dates correspond to the testing of the first three walls. The lower strength of the finish coat is attributed to the increase volume of hydrated lime in the coat. A summary of the compressive strengths of the stucco is provided in Appendix A.2.

(a)

(b)

(c)

(d)

Figure 2.45 **Installation of stucco: (a) applying scratch coat; (b) final scratch coat; (c) final brown coat; and (d) final finish coat.**

2.6 RETROFIT DESIGN AND INSTALLATION

Four of the eleven specimens were retrofitted. Each retrofitted cripple wall had an existing specimen identical in every way besides the addition of the retrofit with the exception of Specimen A-19). It should be noted that Specimen A-19 closely matched Specimen A-20), only differing in terms of its bottom boundary condition (bottom boundary condition “d” for the retrofitted specimen and bottom boundary condition “c” for the unretrofitted specimen). Since the bond between the stucco and the foundation had partially degraded prior to testing, these cripple walls may be nominally considered a retrofit pair. The cripple wall retrofit was designed in accordance with the *FEMA P-1100* prescriptive design provisions.

The *FEMA P-1100* prescriptive design provisions were chosen based on the weight classification, number of stories, height of cripple wall, and square footage of the floor plan as well the seismicity of dwelling’s location. The weight classification is a factor of the materials in the exterior finish, interior finish, and roofing. This produces a light, medium, or heavy weight classification. The flow chart used to determine the weight classification can be seen in Figure 2.46 which is derived from Figure 4.4-1 of *FEMA P-1100*. With the weight classification determined, the length of plywood, number of anchor bolts, plywood edge nailing spacing, and number of shear clips are then determined, and based on the number of stories, square footage, height of cripple wall, S_{DS} of the dwelling, and the presence of tie-downs. The table was used for determining the retrofit design shown in Tables 2.2 and 2.3 for the 2-ft- and 6-ft-tall cripple walls, respectively. These tables are adapted from Figures 4.4-9 of *FEMA P-1100*. The length of plywood, number of anchor bolts, plywood edge nailing spacing, and number of shear clips is that required for each perimeter wall line.

The retrofit design used herein for the cripple wall specimens was based on a model dwelling with plan dimensions of 30 ft × 40 ft. This floor plan was chosen to be in line with the index building used in the ATC-110 project [ATC 2014]. Therefore, the retrofit design for the model building was assumed to be two-stories and 2400 ft^2. For ten of the eleven tests, a heavy gravity load of 450 plf was used with the intention of simulating the gravity weight of two stories above the cripple wall, in addition to heavy building materials. The short-period design spectral response factor, S_{DS}, was assumed to be 1.0*g* (32.17 ft/sec^2). A value of 1.0*g* for S_{DS} is representative of a highly seismic area with ordinary fault conditions—not near-fault conditions. This aligns with the design of the loading protocol used in all tests discussed in this report [Zareian and Lanning 2020]. Lastly, three of the cripple walls were 2 ft high, and one of the cripple walls was 6 ft high. Table 2.2 shows the retrofit design provisions for the 2-ft-tall cripple walls and Table 2.3 shows the retrofit design provisions for the 6-ft-tall cripple walls. Note that in the case of the 6-ft-tall cripple walls, tie-downs were utilized to transfer the large end wall tension forces.

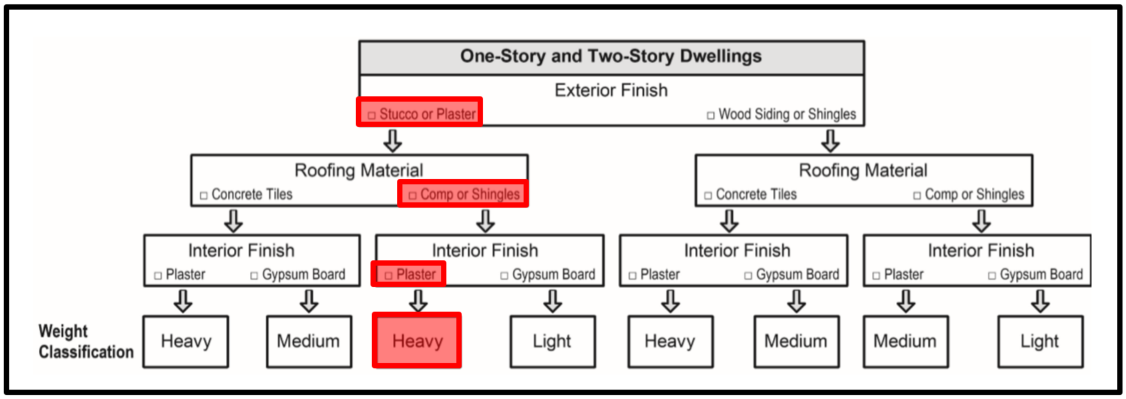


Figure 2.46 ***FEMA P-1100*** **dwelling weight classification flow chart.**

Table 2.2 **Retrofit schedule selection per the recommendations of *FEMA P-1100* for a 2-ft-tall cripple wall retrofit.**

EARTHQUAKE RETROFIT SCHEDULE (S_{DS}= 1.0 Seismic) TWO-STORY

Weight Category	Total Area in Square Feet	☒ Mark row that applies	Length Each of Two Braced Wall Sections Required Along Each Perimeter Wall Line — Plywood Bracing Panels — Cripple Wall Height: up to 1' — Without Tie-downs	1'-1" to 2' — Without Tie-downs	2'-1" to 4'-0" — Without Tie-downs	2'-1" to 4'-0" — With Tie-downs	4'-1" to 6'-0" — Without Tie-downs	4'-1" to 6'-0" — With Tie-downs	6'-1" to 7'-0" — Without Tie-downs	6'-1" to 7'-0" — With Tie-downs	Plywood Edge Nailing	Number of Foundation Connectors or Anchors at Each Perimeter Wall Line Assume Distributed Along Length — Foundation Sill Anchors: Type "A"	Type "B"	Type "C"	1/2"ø Bolt	5/8"ø Bolt	Floor to Cripple Wall or Floor to Foundation Sill: Type "D"	Type "E" or "F"	Type "G"
2-Story Light Construction	up to 1600		8.0'	8.0'	10.7'	8.0'	12.0'	9.3'	13.3'	9.3'	4"	7	10	11	11	8	17	17	22
	1601 to 2000		9.3'	9.3'	12.0'	9.3'	13.3'	10.7'	14.7'	10.7'	4"	8	12	13	13	9	20	19	26
	2001 to 2400		10.7'	10.7'	13.3'	10.7'	14.7'	10.7'	16.0'	12.0'	4"	9	14	15	15	10	23	22	29
	2401 to 3000		12.0'	12.0'	14.7'	12.0'	17.3'	13.3'	18.7'	13.3'	4"	10	16	18	18	12	27	26	34
	3001 to 4000		14.7'	14.7'	17.3'	16.0'	20.0'	16.0'	21.3'	16.0'	4"	13	20	22	22	15	34	32	43
2-Story Medium Construction	up to 1600		8.0'	9.3'	10.7'	8.0'	13.3'	9.3'	13.3'	10.7'	3"	7	11	12	12	9	19	18	24
	1601 to 2000		9.3'	10.7'	12.0'	9.3'	14.7'	10.7'	14.7'	12.0'	3"	9	13	15	15	10	22	22	28
	2001 to 2400		9.3'	10.7'	13.3'	10.7'	16.0'	12.0'	16.0'	13.3'	3"	10	15	17	17	11	26	25	32
	2401 to 3000		10.7'	12.0'	14.7'	12.0'	17.3'	13.3'	18.7'	14.7'	3"	12	18	20	20	14	30	29	39
	3001 to 4000		13.3'	14.7'	17.3'	13.3'	20.0'	16.0'	21.3'	17.3'	3"	14	23	25	25	17	38	36	48
2-Story Heavy Construction	up to 1600		9.3'	9.3'	12.0'	9.3'	13.3'	10.7'	14.7'	12.0'	2"	9	14	16	16	11	24	23	30
	1601 to 2000		9.3'	10.7'	13.3'	10.7'	14.7'	12.0'	16.0'	13.3'	2"	11	17	18	18	13	28	27	35
	2001 to 2400		10.7'	12.0'	14.7'	10.7'	16.0'	13.3'	17.3'	14.7'	2"	12	19	21	21	14	32	31	41
	2401 to 3000		12.0'	13.3'	16.0'	13.3'	18.7'	14.7'	18.7'	16.0'	2"	14	23	25	25	17	38	37	48
	3001 to 4000		13.3'	16.0'	18.7'	14.7'	21.3'	17.3'	22.7'	18.7'	2"	18	28	31	31	21	48	46	60

Table 2.3 Retrofit schedule selection per the recommendations of *FEMA P-1100* for a 6-ft-tall cripple wall retrofit.

EARTHQUAKE RETROFIT SCHEDULE (S_{DS}= 1.0 Seismic) TWO-STORY																			
Weight Category	Total Area in Square Feet	☒ Mark row that applies	Length Each of Two Braced Wall Sections Required Along Each Perimeter Wall Line									Number of Foundation Connectors or Anchors at Each Perimeter Wall Line Assume Distributed Along Length							
			Plywood Bracing Panels									Foundation Sill Anchors					Floor to Cripple Wall or Floor to Foundation Sill		
			Cripple Wall Height								Plywood Edge Nailing								
			up to 1'	1'-1" to 2'	2'-1" to 4'-0"		4'-1" to 6'-0"		6'-1" to 7'-0"										
			Without Tie-downs	Without Tie-downs	Without Tie-downs	With Tie-downs	Without Tie-downs	With Tie-downs	Without Tie-downs	With Tie-downs		Type "A"	Type "B"	Type "C"	1/2"ø Bolt	5/8"ø Bolt	Type "D"	Type "E" or "F"	Type "G"
2-Story Light Construction	up to 1600		8.0'	8.0'	10.7'	8.0'	12.0'	9.3'	13.3'	9.3'	4"	7	10	11	11	8	17	17	22
	1601 to 2000		9.3'	9.3'	12.0'	9.3'	13.3'	10.7'	14.7'	10.7'	4"	8	12	13	13	9	20	19	26
	2001 to 2400		10.7'	10.7'	13.3'	10.7'	14.7'	10.7'	16.0'	12.0'	4"	9	14	15	15	10	23	22	29
	2401 to 3000		12.0'	12.0'	14.7'	12.0'	17.3'	13.3'	18.7'	13.3'	4"	10	16	18	18	12	27	26	34
	3001 to 4000		14.7'	14.7'	17.3'	16.0'	20.0'	16.0'	21.3'	16.0'	4"	13	20	22	22	15	34	32	43
2-Story Medium Construction	up to 1600		8.0'	9.3'	10.7'	8.0'	13.3'	9.3'	13.3'	10.7'	3"	7	11	12	12	9	19	18	24
	1601 to 2000		9.3'	10.7'	12.0'	9.3'	14.7'	10.7'	14.7'	12.0'	3"	9	13	15	15	10	22	22	28
	2001 to 2400		9.3'	10.7'	13.3'	10.7'	16.0'	12.0'	16.0'	13.3'	3"	10	15	17	17	11	26	25	32
	2401 to 3000		10.7'	12.0'	14.7'	12.0'	17.3'	13.3'	18.7'	14.7'	3"	12	18	20	20	14	30	29	39
	3001 to 4000		13.3'	14.7'	17.3'	13.3'	20.0'	16.0'	21.3'	17.3'	3"	14	23	25	25	17	38	36	48
2-Story Heavy Construction	up to 1600		9.3'	9.3'	12.0'	9.3'	13.3'	10.7'	14.7'	12.0'	2"	9	14	16	16	11	24	23	30
	1601 to 2000		9.3'	10.7'	13.3'	10.7'	14.7'	12.0'	16.0'	13.3'	2"	11	17	18	18	13	28	27	35
	2001 to 2400		10.7'	12.0'	14.7'	10.7'	16.0'	13.3'	17.3'	14.7'	2"	12	19	21	21	14	32	31	41
	2401 to 3000		12.0'	13.3'	16.0'	13.3'	18.7'	14.7'	18.7'	16.0'	2"	14	23	25	25	17	38	37	48
	3001 to 4000		13.3'	16.0'	18.7'	14.7'	21.3'	17.3'	22.7'	18.7'	2"	18	28	31	31	21	48	46	60

From the table, the row representing heavy construction for a two-story 2400 ft^2 dwelling was used. The square footage was based on two stories with 1200 ft^2. For the 2-ft-tall cripple walls, 12 ft of wood structural panels, edge nailed at 2 in. on center, were required for a perimeter wall line. The retrofit design consisted of fully sheathed walls with 15/32-in.-thick plywood, edge nailed at 3 in. on center, which essentially provided the same capacity as what the *FEMA P-1100* retrofit prescribed. It was chosen to modify the design to sheath the full length of the specimens.

From Tables 2.2 and 2.3, 21 all-thread, 1/2-in. anchor bolts were required along the perimeter wall, which was 40 ft in length for the model dwelling considered. For the 12-ft section of wall tested, five anchor bolts were used. In addition, *FEMA P-1100* requires an extra anchor bolt at each end of the cripple wall. Five anchor bolts were slotted into the pre-existing anchor bolt slots on the foundation, spaced at 32 in. on center, and the additional two anchor bolts were embedded 10 in. into the foundation and epoxied with Simpson Strong-Tie SET-XP, 12 in. inward from the outer two most anchor bolts, as shown in Figure 2.47. For the 6-ft-tall cripple walls with tie-downs, 13 ft-3 in. of wood structural panels, edge nailed at 2 in. on center, were required for a perimeter wall line. To sheath the full length of the wall, the edge nail spacing was modified to 3 in. on center. Therefore, the 6-ft-tall cripple wall was fully sheathed with 15/32-in.-thick plywood, edge nailed at 3 in. on center. As with the 2-ft-tall specimens, 21 anchor bolts along the perimeter wall were required as per *FEMA P-1100*. For the 6-ft-tall specimen, five anchor bolts were required along with the two additional anchor bolts at each end of the wall. Due to the geometry of the cripple wall and foundation, the location of the anchor bolts attached to the tie-downs did not align with the anchor bolt slots on the foundation. Therefore, these anchor bolts, as well as the additional anchor bolt added at each end, were embedded 10-in. into the foundation and epoxied into place, as shown in Figure 2.48. The remaining three anchor bolts were slotted into the pre-existing anchor bolt slots on the foundation and spaced at 32 in. on center.

Prior to sheathing, 2 × 4 blocking was attached to the sill plate with 4-10d common nails per stud bay. For all cripple wall retrofits in Phase 3, full blocking was used with 4-10d common nails per stud bay. This differs from Phase 2 testing where split blocking was often used. Split blocking involves using two 2 × 4 sections of blocking instead of a full 2 × 4 section to fill the entire stud bay. With this configuration, all the anchor bolts rest on the blocking. Full blocks were placed in stud bays that did not have anchor bolts. An additional 4 × 4 end studs were toe-nailed in with 2-8d common nails top and bottom at each end of the wall, and two interior 4 × 4 studs were toe-nailed in with 2-8d common nails top and bottom at each interior third. The addition of studs and blocking plates were used to allow the plywood panels to be nailed to the cripple wall. The interior of the framing before the application of plywood for a retrofitted specimen can be seen in Figure 2.41 (a) and (b). The plywood used was 15/32-in., Grade 32/16 plywood and was placed in three 4-ft sections, fully sheathing the interior face of the wall. Panels were attached with 8d common nails at 3 in. on center along the edges and 12 in. on center along the field. A 1/8-in. gap was left between panels to allow for expansion and the nails were placed ¾-in. from the panel edge to prevent from nails tearing through the panel edges, as shown in Figure 2.41. Plywood panels terminate at the top of the middle top plate. For the 6-ft-tall cripple wall with horizontal siding, Simpson Strong-Tie HDU4-SDS2.5HDG hold-downs were used for the tie-downs at both ends. The tie-downs are hot dip galvanized and fastened with six 1/4-in. × 2-1/2 in. Strong-Drive SDS screws into the end studs, as seen in Figure 2.42.

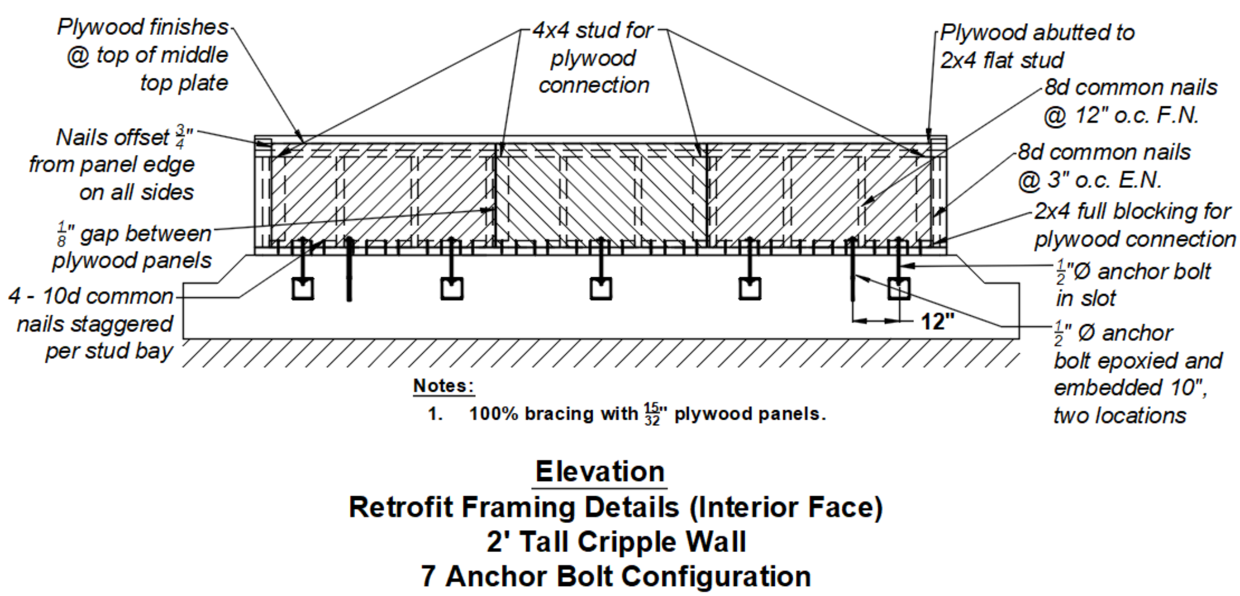
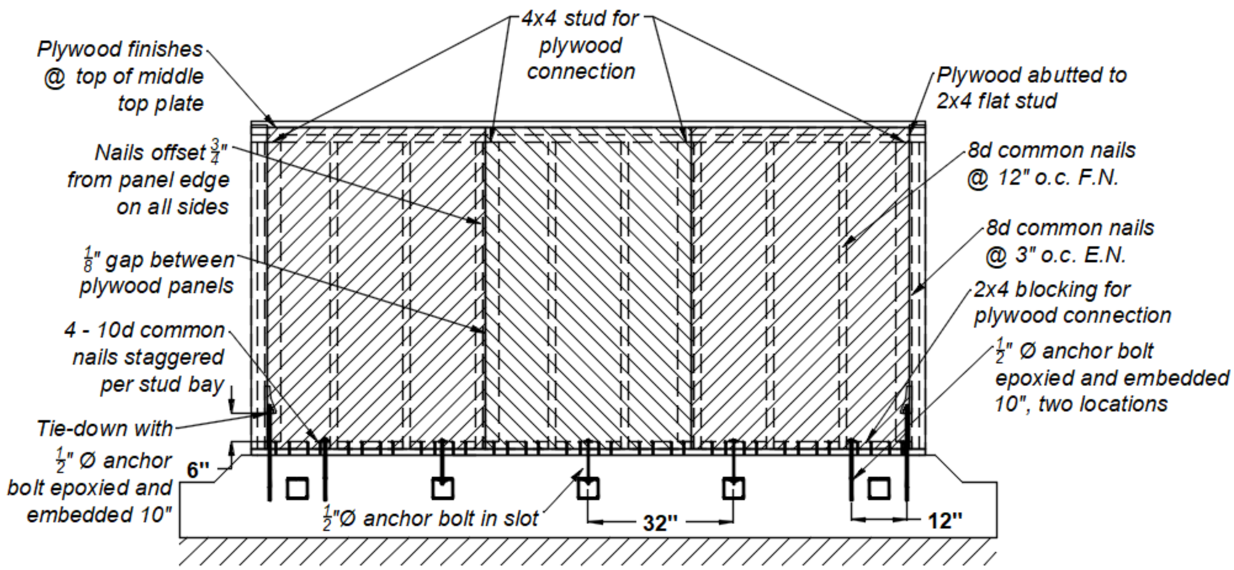


Figure 2.47 **Retrofit design for 2-ft-tall cripples walls.**

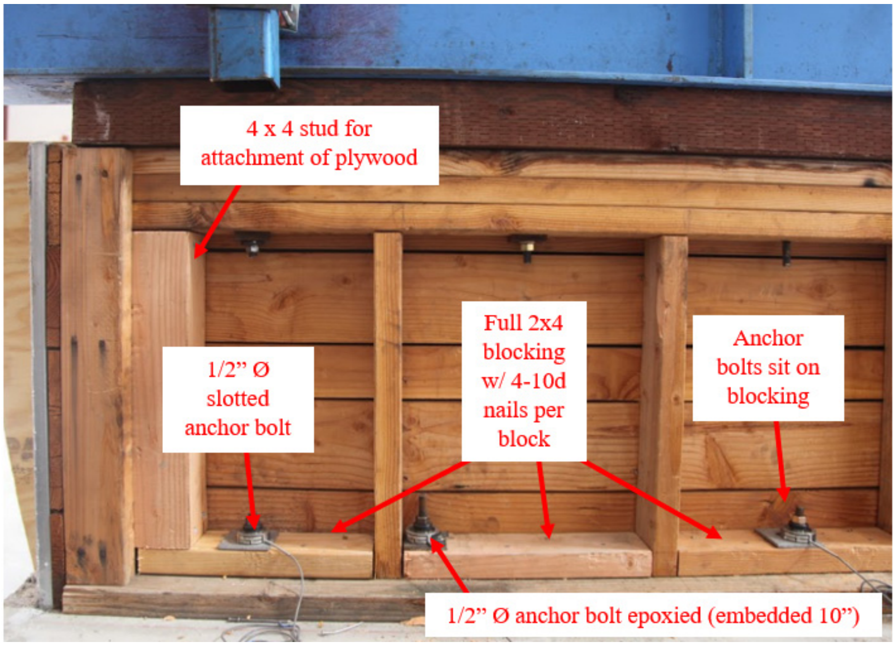


Notes:

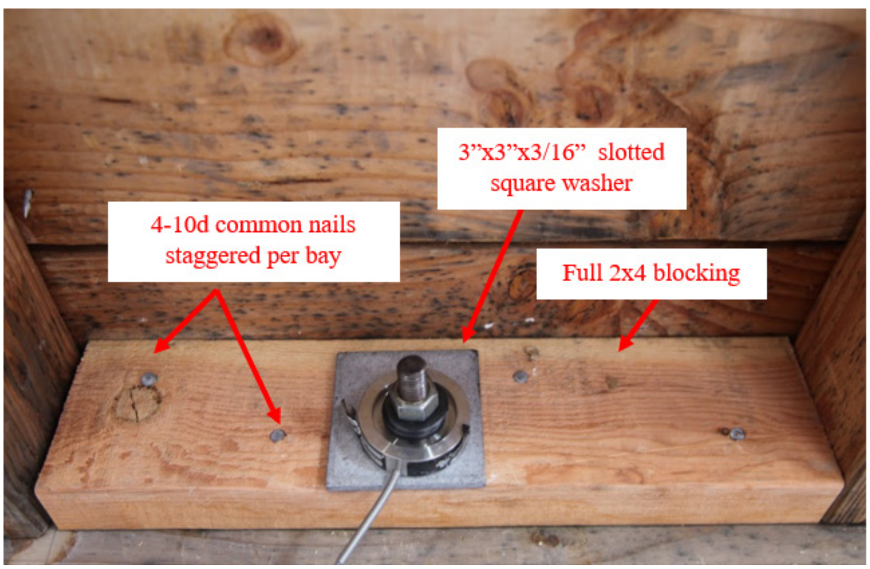
1. 100% bracing with $\frac{15}{32}$" plywood panels.

Elevation
Retrofit Framing Details (Interior Face)
6' Tall Cripple Wall
7 Anchor Bolt Configuration w/ Tie-Downs

Figure 2.48 Specimen A-26 retrofit design for the 6-ft-tall cripple wall with stucco over framing exterior finish.

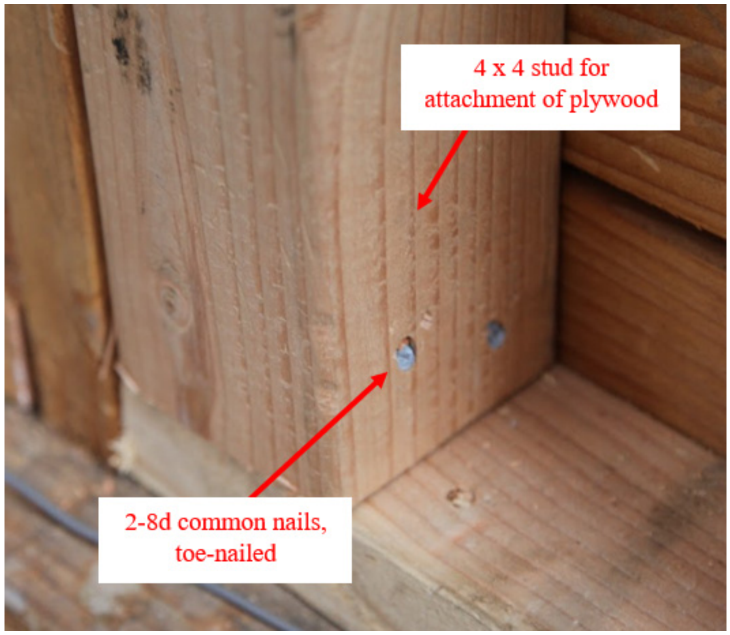


(a)

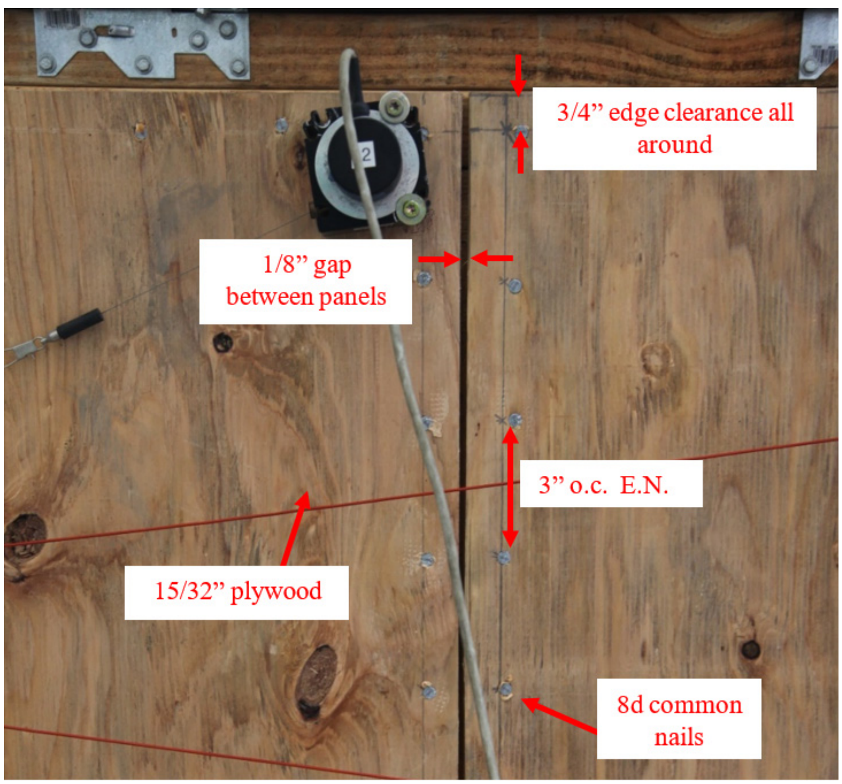


(b)

Figure 2.49 Retrofit application details: (a) framing face corner retrofit detail; (b) view of stud bay; (c) view of added 4 × 4 stud bay; and (d) plywood attachment detail.



(c)



(d)

Figure 2.49 (continued).

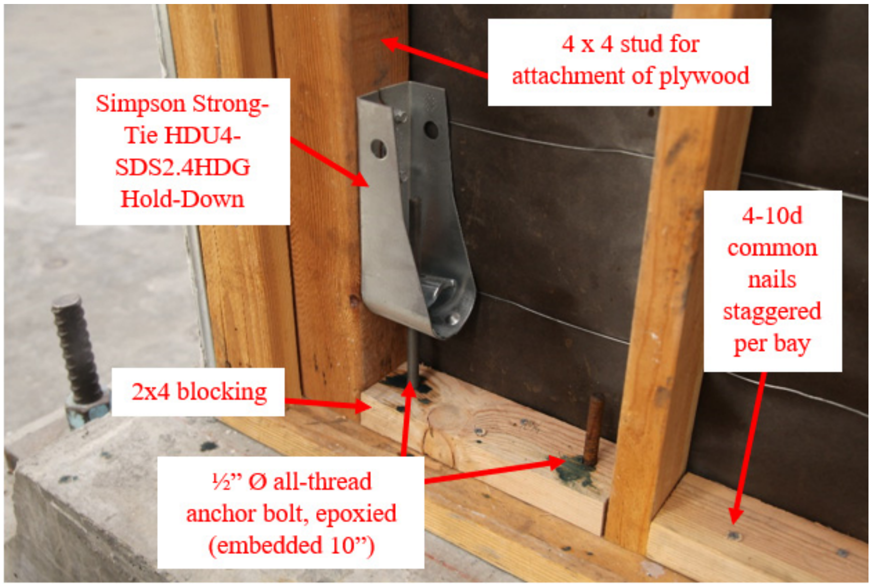
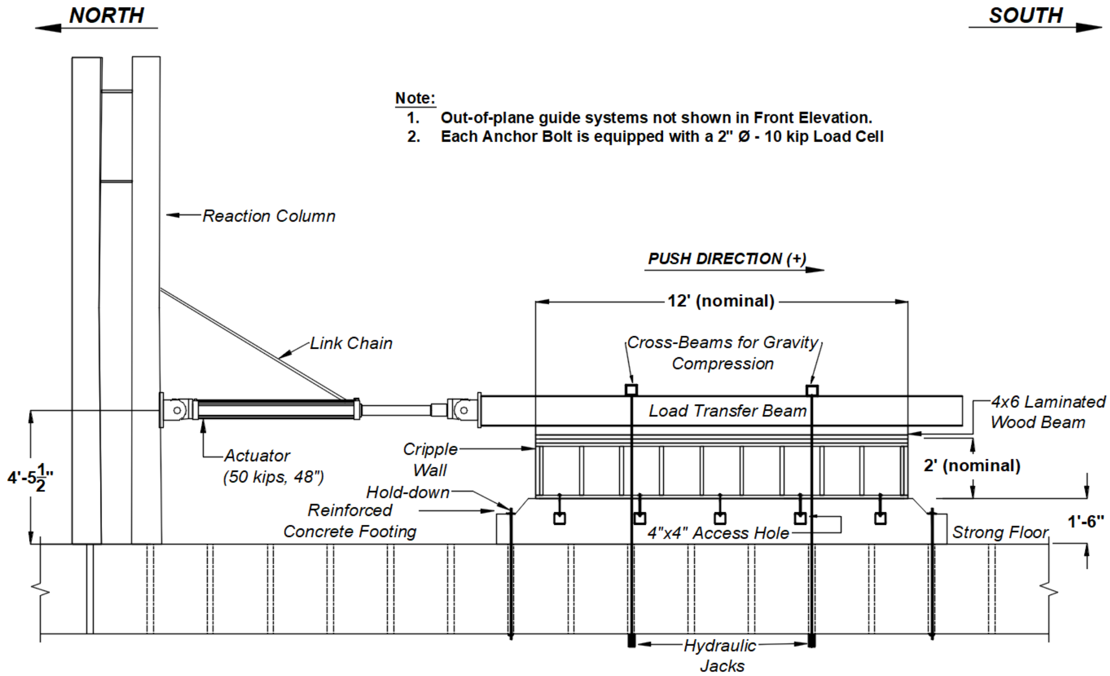


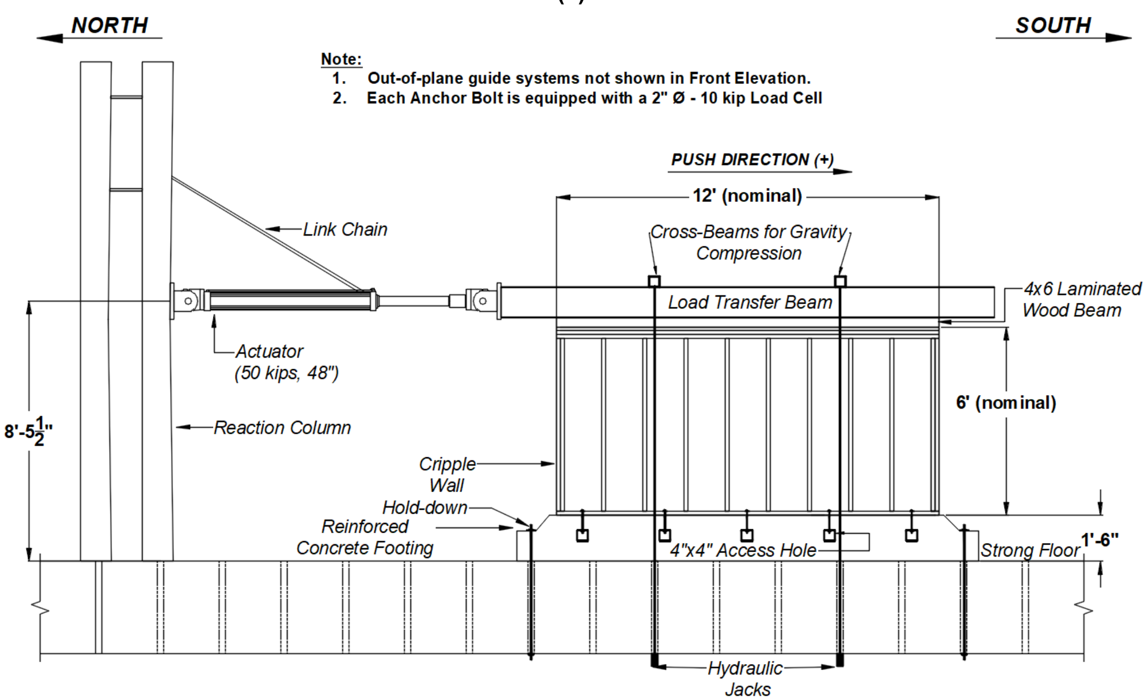
Figure 2.50 Specimen A-25 tie-down placement.

2.7 TEST SETUP

Figure 2.51 shows a plan view and elevations view 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 2.52. 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 (when present in retrofitted walls), during testing a 4 × 6 laminated 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. A 1-in. × 1-in. notch was cut out of the laminated wood beam to allow for the exterior finish materials to freely rotate. Details of the connection of the steel beam, laminated wood beam, and cripple wall framing can be seen in Figure 2.53. The connection from the steel beam to the laminated wood beam was made with pairs of 3/8-in. diameter by 3-1/2-in. long lag bolts at 16 in. on center, connected from the bottom flange of the steel beam top of the wood beam. The laminated wood beam was selected to be sufficiently thick as to preclude connection between the lag bolts and the cripple wall top plates. The cripple wall specimens were connected to the laminated wood beam using 1/2-in-diameter by 7-1/2-in.-long, Grade 2 steel thru bolts at 32 in. on center. These bolts were countersunk into the laminated wood beam and fastened with nuts and washers at the bottom of the lowermost top plate.



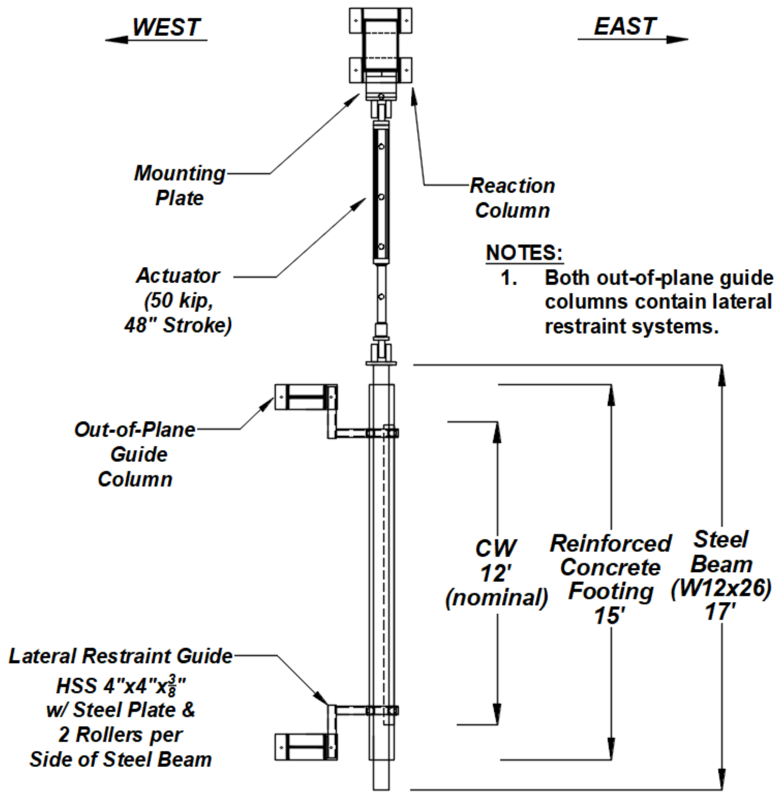
Elevation
2' Tall Cripple Wall Test Setup
(a)



Elevation
6' Tall Cripple Wall Test Setup

(b)

Figure 2.51 **Test setup: (a) elevation of basic test setup for the 2-ft-tall cripple wall; (b) elevation of basic test setup for the 6-ft-tall cripple wall; and (c) plan view of basic test setup.**



Plan View
Cripple Wall Test Setup

(c)

Figure 2.51 (continued).

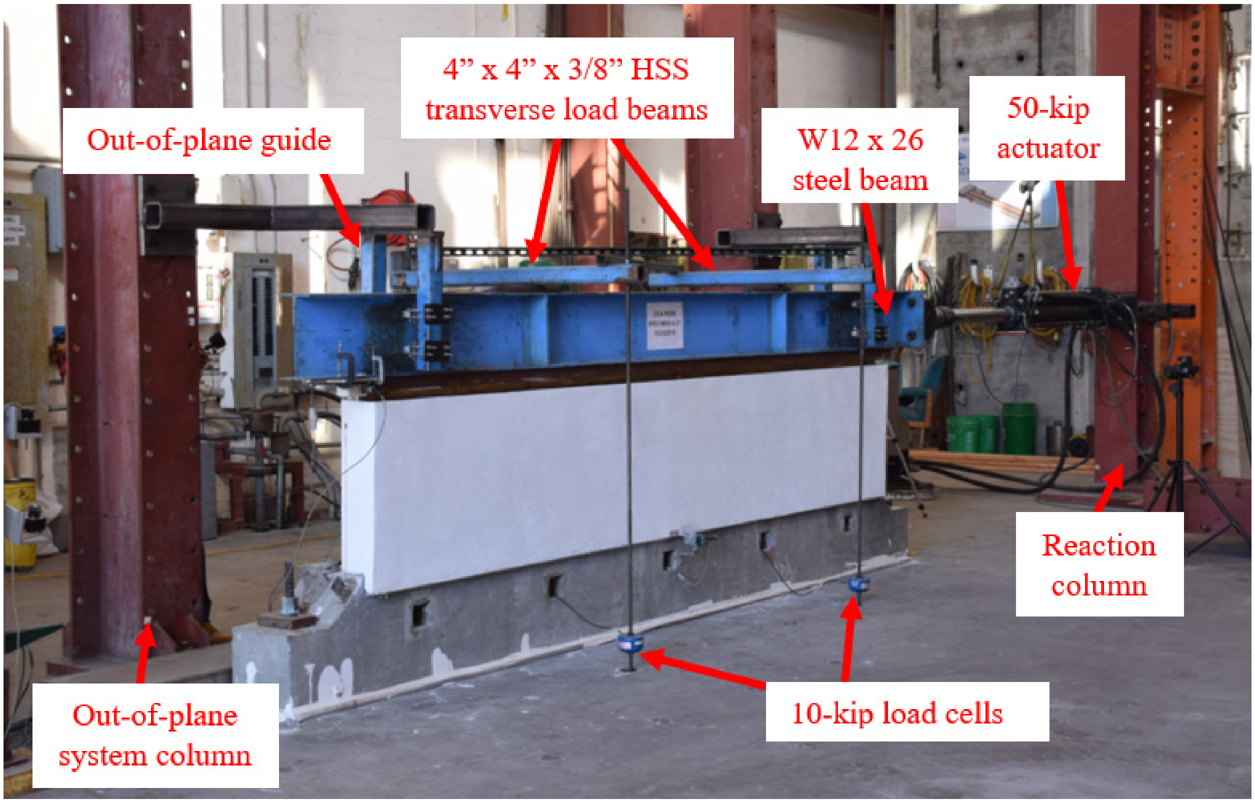


Figure 2.52 Isotropic view of the test setup for 2-ft-tall cripple walls.

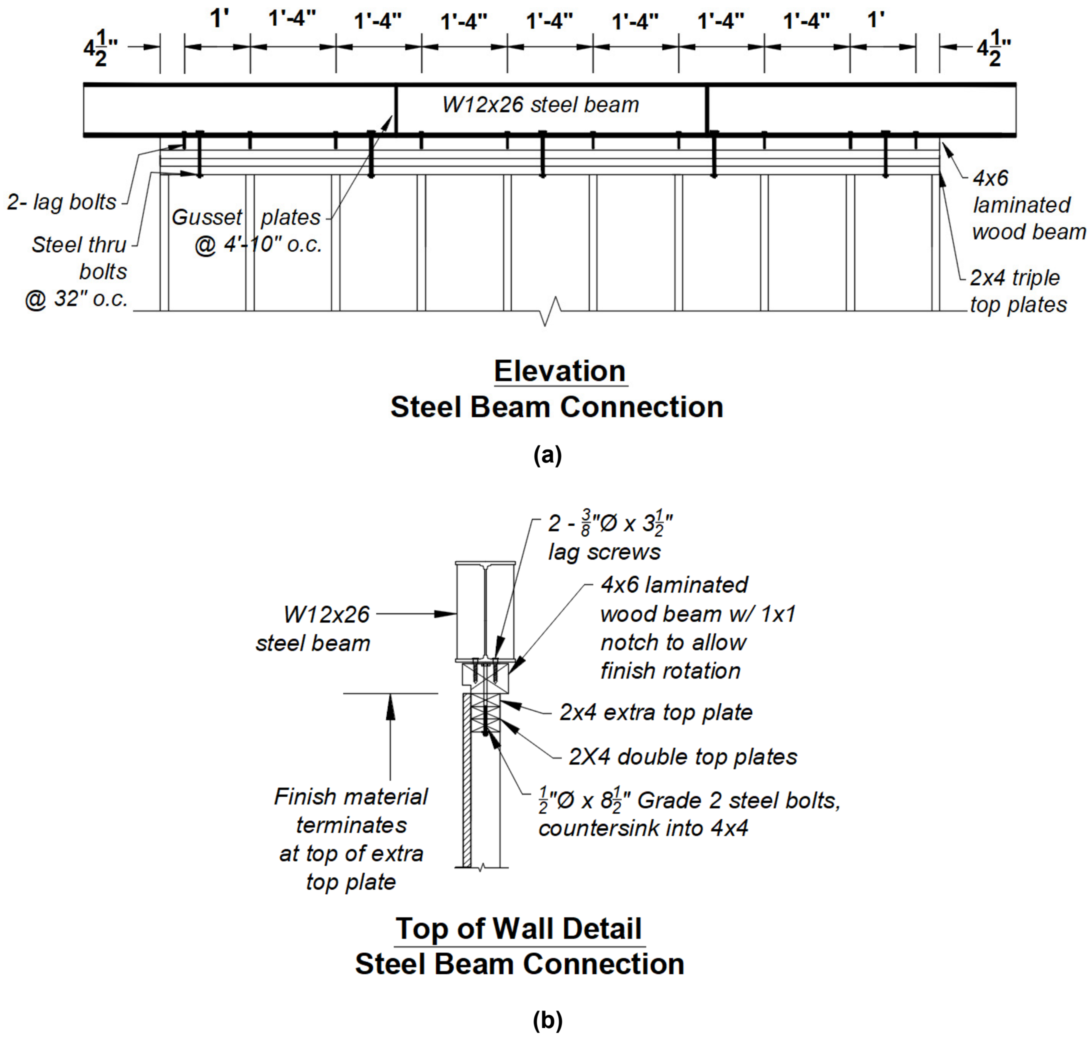


Figure 2.53 **Horizontal steel beam to cripple wall connection details: (a) elevation of steel beam connection; and (b) top of wall detail.**

When possible, the concrete footing was reused for each test as it was fastened to the strong floor with a rod at each end, each tensioned to 50 kips. Individual dry finished specimens were constructed on the laboratory floor and erected onto the concrete footing; subsequently, the laminated wood beam and steel beam were attached. After these beams were attached, the actuator was attached with four 1-in. diameter bolts. Subsequently, two 4 in. × 4 in. × 3/8 in. HSS sections were placed transversely at every 1/3 points along the specimen 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 thread rods were attached to hydraulic jacks at the base of the strong floor. The hydraulic jacks were used to apply the desired vertical load to each specimen. The location of the transverse beams can be seen in Figures 2.51 and 2.52. The choice of location for applying the loads was meant to result in an approximately uniformly distributed gravity load on the full length of the cripple wall specimen. It is noted that while additional point loads would have increased the uniformity of the load distribution, they would have also increased the complexity significantly. In addition, 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. Each thread rod at the HSS transverse beam load locations were equipped with a 10-kip load cell that monitored the applied vertical load during testing.

Every cripple wall was subjected to a constant uniform vertical load of 450 lbs/ft (5400 lbs total). The weight of the steel transfer beam, laminated wood transfer beam, and the transverse vertical loading beams coupled with the use of a pair of hydraulic jacks tied to the bottom of the strong floor was cumulatively utilized to achieve this target vertical load. 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. The necessary load required of the hydraulic jacks was 1.25 kips each for a total of 5 kips. Due to eccentricity of the walls when constructed with bottom boundary condition "c", the applied loads measured were not always 1.25 kips each. Loads ranged from 1.15 kips to 1.40 kips for each hydraulic jack, with 4.8 kips to 5.0 kips for the sum of all hydraulic jacks.

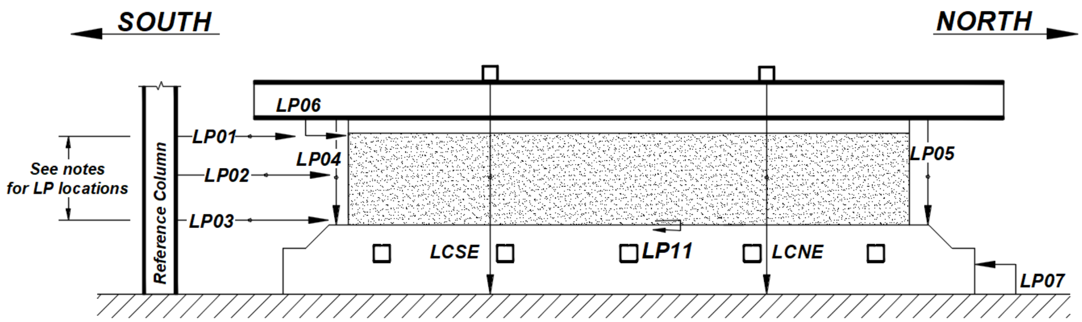
Before any loads were applied to the cripple wall, pairs of rollers were fastened to the sides of the out-of-plane guide, as shown in Figures 2.51 and 2.52. The rollers were greased, and a 1/16-in. gap was left between the steel plate and the steel transfer beam as to not impose any artificial loads 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 was only in-plane.

Once the load was applied to the test setup, the anchor bolts were tensioned. For all tests in this report, 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, which 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. At this point, the test would begin. The lateral displacements imposed are described in the previous chapter.

2.8 INSTRUMENTATION

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. Figure 3.54 shows the instrumentation details for Specimen A-19 and Specimen A-20, 2-ft-tall cripple walls with stucco over horizontal sheathing exterior finish. The difference between the two specimens is as follows: Specimen A-19 was retrofitted while Specimen A-20 was existing: Figure 3.54(b) applies to Specimen A-20, and Figure 3.54(c) applies to Specimen A-19. Figure 3.54 shows the instrumentation details for Specimen A-25 and Specimen A-26, 6-ft-tall cripple walls with stucco over framing exterior finish. Note that Specimen A-25 is an existing specimen, while A-26 is a retrofitted specimen. Therefore, Figure 3.55(b) applies to Specimen A-25, and Figure 3.55(c) applies to Specimen A-26. The complete instrumentation details for all cripple wall specimens can be seen in Appendix B.1.

The overall response of the cripple wall was characterized using displacements measured by displacement transducer LP01. LP01 along with transducers LP02 and LP03 were connected to a stationary reference column tensioned into strong floor. LP01 was attached to the top of the middle top plate, 24 in. from the top of the concrete footing, and captured the total displacement at the top of the cripple wall. LP02 was attached to the middle of the cripple wall, 12 in. from the top of the footing. This intermediate displacement transducer was used to define the deflected shape of the cripple wall. LP03 was attached to the middle of the sill plate to measure the absolute displacement of the sill plate. By taking the difference between LP01 and LP03, the relative displacement of the cripple wall could be determined (neglecting sill-to-foundation displacement). Details of these transducers can be seen in Figure 3.54(a). A photograph of the placement of LP01–LP03 for a 2-ft-tall cripple wall can be seen in Figure 3.56(a). For a 6-ft-tall cripple wall, LP01 was connected to the middle of the upper top plate (72 in. from the top of the concrete footing) and LP03 was connected to the middle of the sill plate. LP02 was placed in the middle of the cripple wall, 36 in. from the top of the concrete footing. A photograph of the placement of LP01–LP03 for a 6-ft-tall cripple wall is shown in Figure 2.56(b).

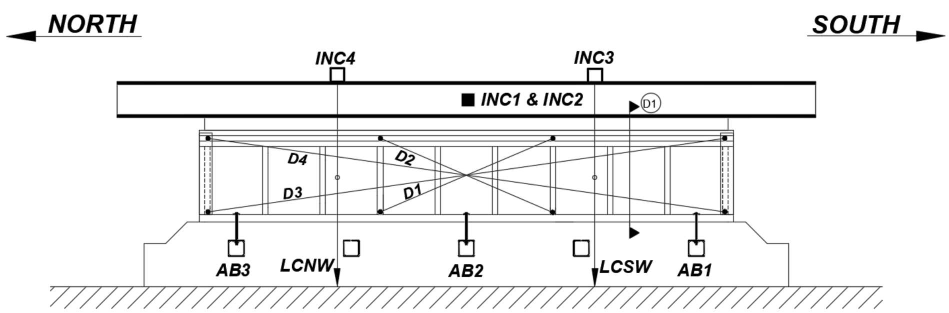


Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of upper top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LP11 monitors the out-of-plane movement of the stucco,
6. LCNE and LCSE monitor the axial load on the East Side of the wall.

Instrumentation Elevation
Stucco Face
2' Tall Cripple Wall

(a)



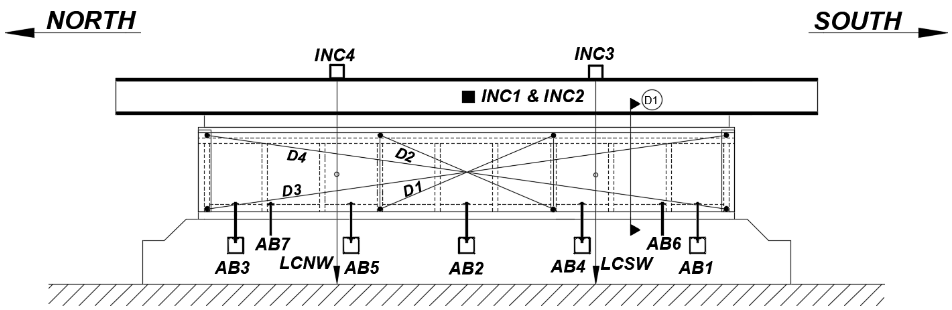
Notes:

1. AB1-AB3 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. INC3 and INC4 measure the rotation of the transverse beams where axial load is applied.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation
Framing Face
2' Tall Un-retrofitted Cripple Wall

(b)

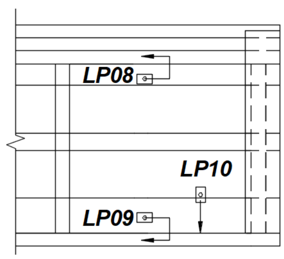
Figure 2.54 Instrumentation details for 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish: (a) exterior elevation; (b) interior elevation of existing cripple wall; (c) interior elevation of retrofitted specimen; and (d) siding instrumentation details.



Notes:
1. AB1-AB7 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. INC3 and INC4 measure the rotation of the transverse beams where axial load is applied.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

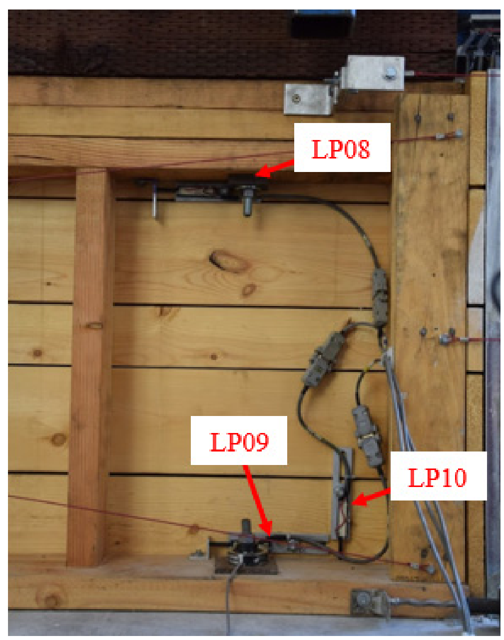
Instrumentation Elevation
Framing Face
2' Tall Retrofitted Cripple Wall

(c)



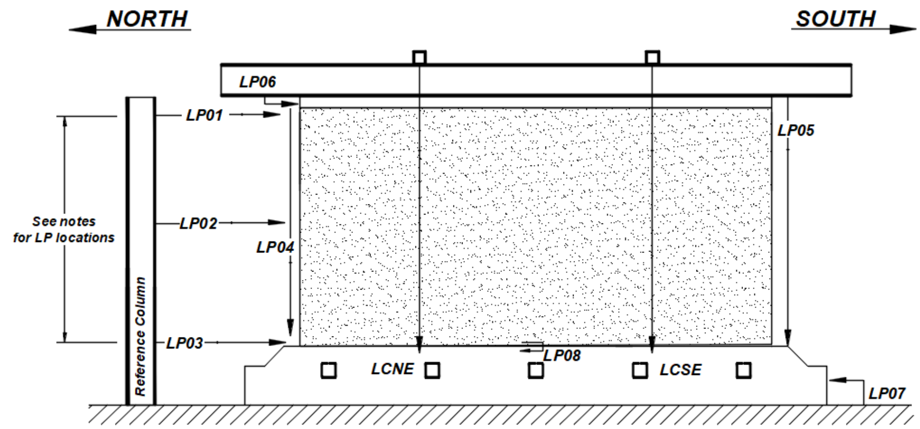
Notes:
1. LP08 and LP09 monitor the siding slip.
2. LP10 monitors the uplift of the bottom sheathing board.

Instrumentation Detail
Siding



(d)

Figure 2.54 (continued).

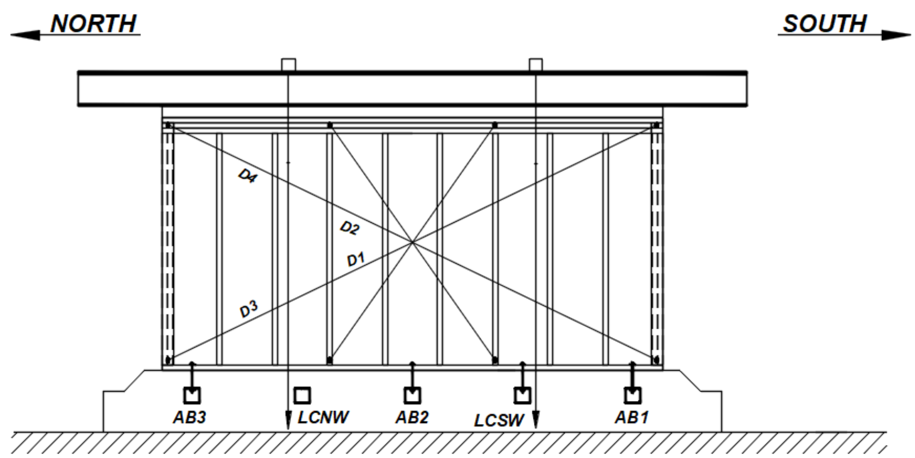


Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of second top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LCNE and LCSE monitor the axial load on the East Side of the wall.
6. LP08 monitors displacement of stucco relative to the footing.

Instrumentation Elevation
Stucco Face
6' Tall Cripple Wall

(a)



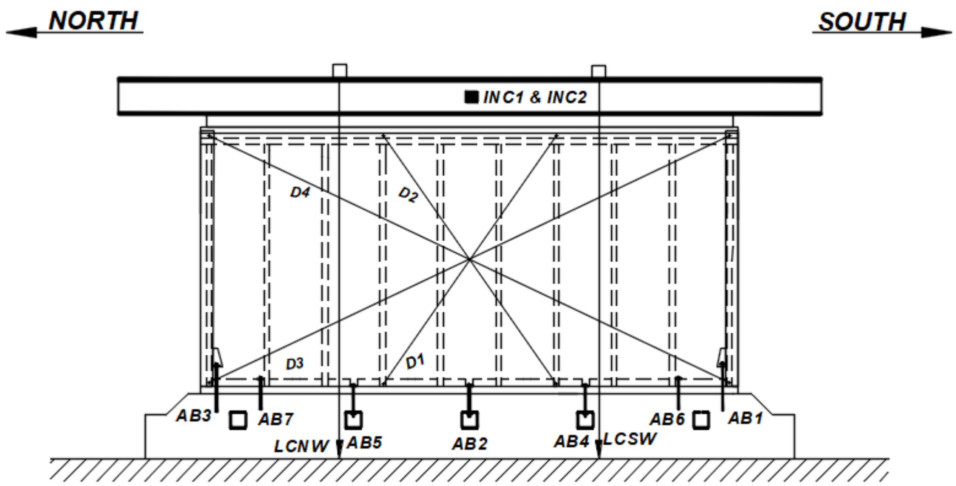
Notes:

1. AB1-AB3 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. D1-D4 measure the diagonal distortion of the wall.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation
Framing Face
Un-retrofitted 6' Tall Cripple Wall

(b)

Figure 2.55 Instrumentation details for 6-ft-tall cripple wall with stucco exterior finish: (a) exterior elevation; (b) interior elevation of existing cripple wall; and (c) interior elevation of retrofitted specimen.



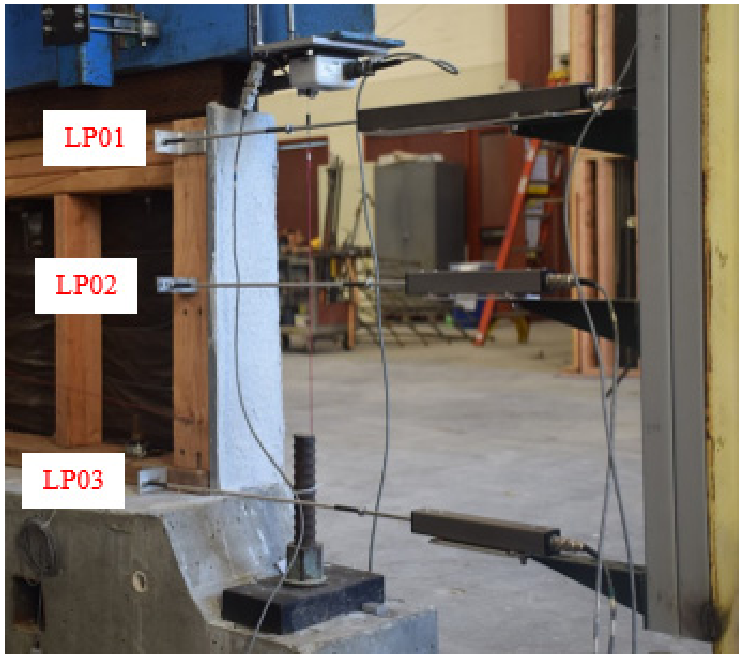
Notes:

1. AB1-AB7 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. D1-D4 measure the diagonal distortion of the wall.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

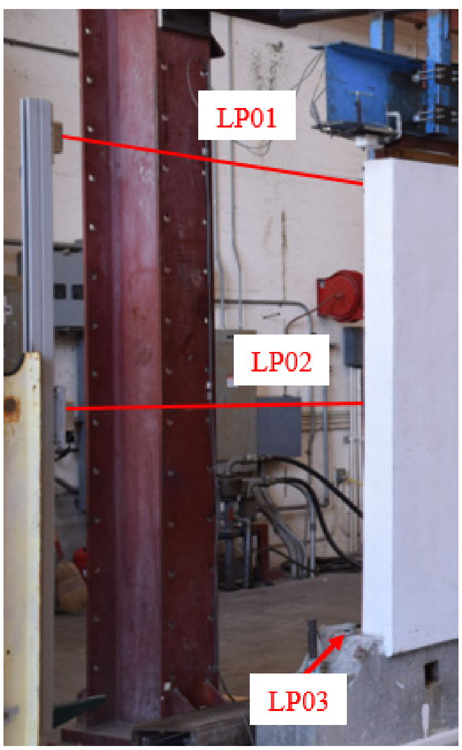
Instrumentation Elevation
Framing Face
Retrofitted 6' Tall Cripple Wall

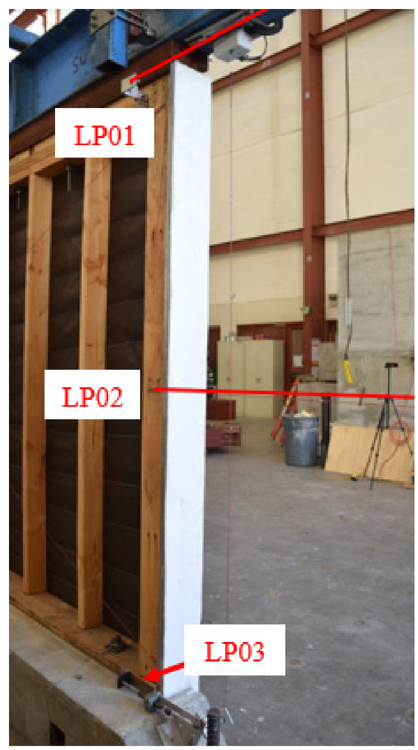
(c)

Figure 2.55 (continued).



(a)





(b) (c)

Figure 2.56 Displacement transducers LP01 – LP03 placement: (a) 2-ft-tall cripple wall; and (b) 6-ft-tall cripple wall.

Local deformations of the cripple wall were also measured. For retrofitted cripple walls, plywood panel deformations of the interior panel and all three panels were determined with two pairs of diagonal displacement transducers, denoted as D1–D4. For existing cases, the diagonal transducers were fastened to the framing on the top and bottom of studs for the interior transducers and the flat corner studs for the outer transducers. The location of these diagonal transducers can be seen in Figures 2.54(b) and 2.55(b). The inner diagonal transducers, D1 and D2, characterized the distortion of the middle 4-ft section of the wall or the middle plywood panel when the cripple wall was retrofitted. For the retrofitted cases, the shear distortion of the middle panel was smaller than the resolution of the displacement transducers. The outer diagonal transducers, D3 and D4, characterized the overall distortion of the entire cripple wall.

Uplift of the cripple wall was measured at each end with displacement transducers LP04 and LP05, as shown in Figures 2.54(a) and 2.55(a). For 2-ft-tall cripple walls, the uplift measurements were also out of the resolution range of the transducers. This is not expected to be the case with 6-ft-tall cripple wall specimens. The slip between the steel transfer beam and the uppermost top plate was measured by LP06. It should be noted that even if slip between steel transfer beam and top plate occurred, it did not affect the amount of displacement imposed on the cripple wall specimen, as that is controlled by LP01, which is attached to the cripple walls itself. LP07 is a displacement transducer attached to the strong floor, measuring the slip between the foundation and strong floor. The foundation was tensioned to ensure that no slip occurred at this interface.

Two inclinometers denoted as INC3 and INC4, were attached to the east end of the transverse vertical load beams to measure rotations of the beams during loading. Each transverse load beam was tensioned through a thread rod and a hydraulic jack fastened under the strong floor. Each thread rod was connected to a 10-kip load cell used to monitor the vertical load imposed. These load cells are shown in Figure 2.54(a) and (b) (for the 2-ft-tall cripple wall) and Figure 2.55(a) and (b) (for the 6-ft-tall cripple wall), and labeled according to their cardinal directional position (i.e., LCNW for the northwest load cell). The use of these four displacement transducers, two inclinometers, and four load cells monitored both the vertical load applied to the specimen and the lateral load imposed due to the horizontal component of the displacing vertical load. This artificial horizontal load component is taken out of the lateral responses of each cripple wall.

The tension in each anchor bolt was measured with a 10-kip donut load cell. These load cells also monitored the uplift forces in the cripple wall. The setup of these load cells is discussed in Section 2.2. Finally, two inclinometers, INC1 and INC2, measured the rotation of the horizontal load transfer beam along the longitudinal and transverse axis of the loading direction. Additional displacement transducers measured important displacements on various components of the cripple wall. As seen in Figures 2.54(c) and 2.55(c), LP10 measured the uplift of the bottom siding board. LP08 and LP09 measured the horizontal displacement of the top siding board and the bottom siding board, respectively.

As mentioned before, there were small variations in the instrumentation of some of the cripple wall specimens depending on the exterior finish and the retrofit condition. These variations can be seen in Appendix B.1.

2.9 CAMERA VIEWS

For each test, extensive high-resolution digital photographs and video documentation were taken to document the pre-test, during testing, and post-test state of each cripple wall specimen. During testing, photographs were taken at the push and the pull loading of the first cycle for each drift ratio level, as well as at the end of the last cycle of the drift ratio level for the 0.2%–1.4% drift amplitudes. Five to six cameras were used to capture the live motion of the cripple wall during testing. Figure 2.57 shows the locations of each of the cameras used to record tests. One of the cameras was a live web camera with views of the finish face of the cripple wall. These tests recorded the test continuously from start to finish. During video processing, the recordings of the webcams were edited and overlaid with the loading protocol as well as the lateral force–lateral displacement hysteresis of the cripple wall. The other three to four cameras worked to capture various angles of the walls that were deemed most important to help understand the behavior of the specimen during testing. The framing face and finish face were often recorded with these cameras as well because the video resolution of these cameras is higher than that of the webcams. Other important areas that were visually documented were the ends of the cripple walls. All cripple walls would bear on the foundation at their ends, which caused these areas to accumulate more significant damage than the framing or finish faces, especially at low drift amplitudes.

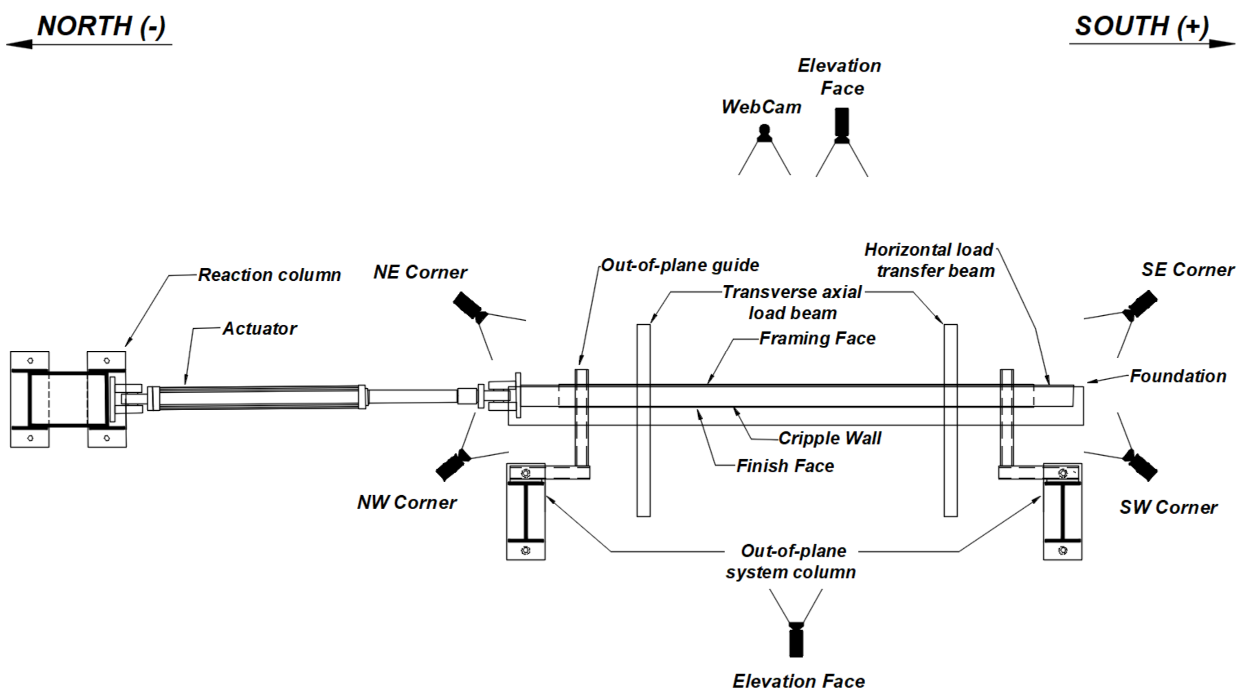


Figure 2.57 Layout of cameras and scope of view.

2.10 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 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 vary slightly depending on instrumentation constraints. Figure 2.58 shows the loading protocol for Specimen A-19 (a 2-ft-tall cripple wall), and Table 2.4 gives details of the loading protocol. Figure 2.59 shows the loading protocol for Specimen A-25 (a 6-ft-tall cripple wall), and Table 2.5 gives details of the loading protocol. Details of the loading protocol for each test can be seen in Appendix A.3, and the background to the protocol development may be found in Zareian et al. [2020]. It is noted that the aforementioned protocol is consistent with that utilized for all other specimens throughout the complete UC San Diego test program.

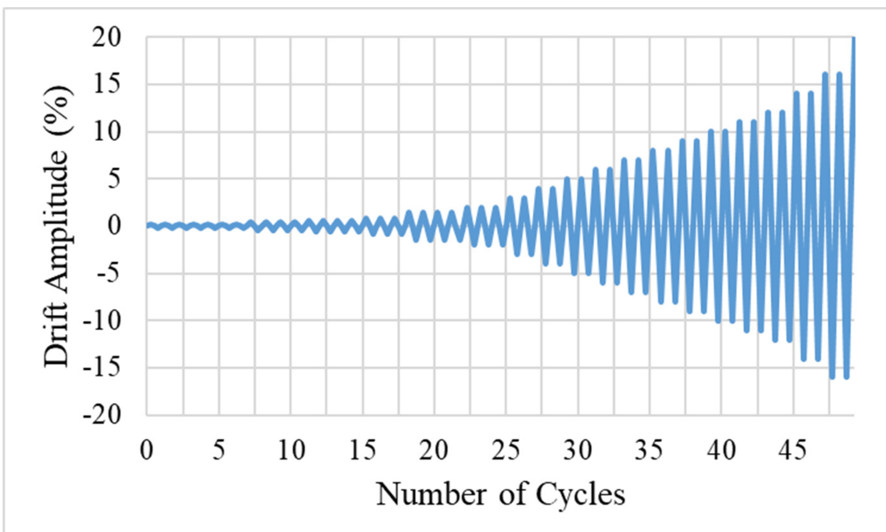


Figure 2.58 Specimen A-19 loading protocol (2-ft-tall specimen).

Table 2.4 Specimen A-19 summary of loading protocol for the 2-ft-tall specimen.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	7	1.68	2	0.224	30	60
12	8	1.92	2	0.256	30	60
13	9	2.16	2	0.288	30	60
14	10	2.4	2	0.16	60	120
15	11	2.64	2	0.176	60	120
16	12	2.88	2	0.192	60	120
17	14	3.36	2	0.224	60	120
18	16	3.84	2	0.256	60	120
19	Mono	5.0	--	0.333	60	60

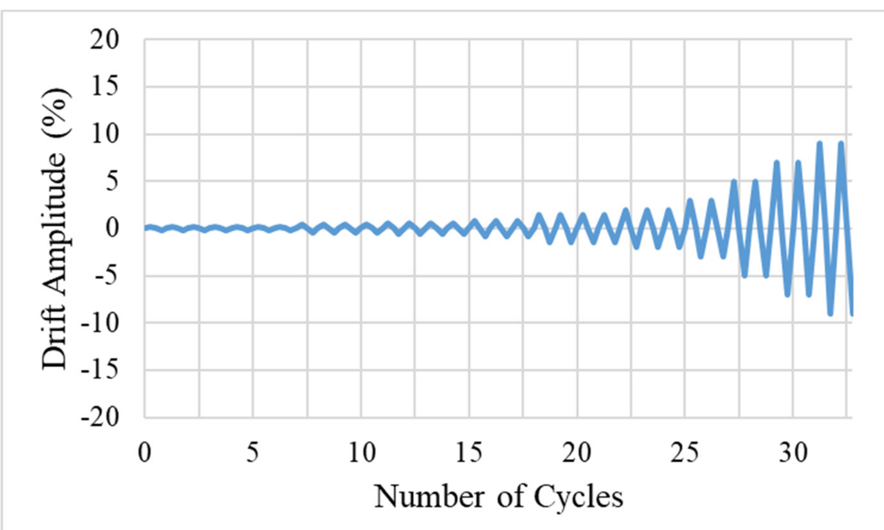


Figure 2.59 Specimen A-25 loading protocol (6-ft-tall specimen).

Table 2.5 Specimen A-25 summary of loading protocol (6-ft-tall specimen).

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	9	6.48	2	0.216	120	240

3 Test Results

3.1 GENERAL

This chapter presents the results of reversed cyclic response of the eleven wet (stucco) finished cripple walls in the testing program. The key parameters of interest in this testing program are exterior finish, height, boundary condition to the bottom of the wall, loading protocol, anchorage condition, and retrofit condition of the cripple walls. The boundary conditions of the top and corners of the specimens, vertical load, and length of the cripple walls remained constant for all eight tests. As stated in the previous chapter, each cripple wall is around 12 ft long and either 2 ft tall (9 specimens) or 6 ft tall (2 specimens). Each wall was subjected to a vertical load of 450 lbs/ft, mimicking the gravity load of a typical two-story house, and all the walls had top boundary condition B and bottom boundary condition “c” or “d”. The effect of bottom boundary condition “c” versus bottom boundary condition “d” on the response of the cripple wall is discussed. The details of these boundary conditions can be seen in Section 2.2.2. Evaluated are the effects of the various exterior finishes: (1) stucco over framing; (2) stucco over horizontal lumber sheathing; and (3) stucco over diagonal lumber sheathing. In addition, also evaluate is the performance of a retrofitted cripple wall considering the variation of height (2-ft-tall versus 6-ft-tall). Lastly, the effects of changes in the anchorage condition and the loading protocol are presented. Table 3.1 presents the variables subject to change for each test. In addition, a pseudo-name is given to each of the specimens for purposes of clarity in the presentation of the results.

Table 3.1 Variable parameters for each cripple wall tested and specimen pseudo-names.

Specimen name	Test no.	Description of test	Specimen pseudo-name
A-15	20	Stucco over diagonal sheathing, existing, bottom BC: c, 2 ft tall	2' S[1]+ DSh[2]
A-16	21	Stucco over diagonal sheathing, retrofitted, bottom BC: c, 2 ft tall	2' S+DSh Retrofit
A-17	18	Stucco, existing, bottom BC: d, 2 ft tall l	2' S (d)[4]
A-18	22	Stucco, retrofitted, bottom BC: d, 2 ft tall	2' S Retrofit (d)
A-19	19	Stucco over horizontal sheathing, retrofitted, bottom BC: c, 2 ft tall l	2' S+HSh[3] Retrofit
A-20	15	Stucco over horizontal sheathing, existing, bottom BC: d, 2 ft tall	2' S+HSh (d)
A-21	17	Stucco over horizontal sheathing, existing, wet set sill, bottom BC: c, 2 ft tall	2' S+HSh WS[5]
A-22	16	Stucco, existing, bottom BC: c, 2 ft tall	2' S
A-25	26	Stucco, existing, bottom BC: c, 6 ft tall	6' S
A-26	27	Stucco, retrofitted, bottom BC: c, 6 ft tall	6' S Retrofit
A-27	28	Stucco over horizontal sheathing, existing, monotonic ,bottom BC: c, 2 ft tall	2' S+HSh M[6]

[1] S = Stucco.
[2] DSh = Diagonal sheathing.
[3] HSh = Horizontal sheathing.
[4] (d) = Bottom boundary condition "d".
[5] WS = Wet set sill plate.
[6] M = Monotonic loading.

3.2 LATERAL FORCE–LATERAL DISPLACEMENT RESPONSE

This section presents the global lateral force-displacement response of each of the specimens tested in Phase 3 and all wet finished specimens tested in Phase 4. The presentation includes photographs of each specimen, followed by the lateral force-displacement hysteresis; see Figures 3.1 through 3.32. 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, ignoring displacement between the foundation and the sill plate. In addition, secondary axes are 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). It should be noted that maximum lateral load in the positive and negative directions are identified in each hysteresis. The discussions regarding the individual hysteresis are augmented by a cross comparison amongst the various specimens, with particular emphasis on eliciting the impact of the parameters varied. In this regard, a cross comparison of all specimens is first provided, followed by a discussion of the effect of individual parameters considered herein. In later sections, the effect of the *FEMA P-1100* retrofit will be analyzed as well as the effect of cyclic versus monotonic loading.

3.2.1 Summary of Response of All Specimens

Figure 3.33 compares the lateral strength per lineal foot of wall in the push and pull direction for the eleven cripple walls, while Figures 3.34 and 3.35 show the global and relative drift ratios, respectively, at lateral strength in both directions. Important information on the response can be found in the pre- and post-lateral strength behavior; therefore, Figure 3.36 provides a generic monotonic response to illustrate the selected pre- and post- strength values shown in subsequent figures. Figure 3.37 compares the relative drift ratio of each specimen at 80% of the pre-lateral strength, and Figure 3.38 compares the relative drift ratio of each wall at 40% of the post-lateral strength (i.e., 40% residual strength). Finally, Figure 3.39 shows the initial secant stiffness for all six specimens. It is noted that the secant stiffness is defined as the slope from the origin to a point on the pre-strength portion of the envelope that is equal to 80% of the maximum lateral load for the relative displacement response.

With respect to the comparison of lateral strength per Figure 3.33, the lateral strength in both the push and pull directions were close to the equal for many specimens. Both of the 6-ft-tall cripple wall finished with stucco over framing exhibited slightly higher lateral strength in the push loading direction than the pull loading direction (8–12% larger). All cripple walls finished with stucco over horizontal sheathing had lateral loads 5–10% higher in the push direction than the pull direction. This can be attributed the walls being initially loaded in the push direction, resulting in damage on the walls before they were loaded in the pull direction.

Contrasting the global and relative drift ratio at lateral strength of the walls, Figures 3.34 and 3.35, indicate that all 2-ft-tall cripple walls with existing condition anchorage showed significant differences in the global and relative displacement response of the walls due to the displacement of the sill plate relative to the foundation. The cripple wall with the wet set sill plate did not have any differences in its global and relative response as its sill plate was confined on all sides by concrete, which prevented any sill displacement. It is noted that no damage to the concrete surrounding the wet set sill was observed during the testing of this specimen. There was little difference between the global and relative response of the 6-ft-tall cripple walls with stucco finishes. For all 2-ft-tall specimens, the higher the strength of the specimen, the larger the difference between the global and relative response. Larger imposed loads would instigate sliding of the sill plate on the foundation as the frictional force between the sill plate and the top of the foundation would be overcome. The earlier in the loading protocol when the capacity of the cripple walls exceeded the frictional resistance, the larger the relative displacement between the sill plate and the foundation.

A cross comparison of all 2-ft-tall cripple walls demonstrates that the lateral strength—when considering both the push and pull directions—occurred between 2–5% global drift ratio for the existing specimens and 4–8% global drift ratio for the retrofitted specimens. Considering the relative response, the ranges narrowed to 1.1–3% relative drift ratio for the existing specimens and 2.1–5.3% relative drift ratio for the retrofitted specimens. Because the retrofitted cripple wall finished with stucco over diagonal sheathing failed due to fracture of its anchor bolts, it never achieved full strength. If this specimen is removed from the dataset, the relative drift ratio for the retrofitted 2-ft-tall specimens at lateral strength occurred at between 4.5–5.3% relative drift. For the 6-ft-tall cripple walls with stucco exterior finish, the existing specimen achieved strength at 1.4% global drift ratio and 1.0–1.1% relative drift ratio, while the retrofitted specimen achieved strength at 3% global drift ratio and 2.9% relative drift ratio. The monotonically loaded specimen (Specimen A-27, the existing 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish) reached strength at 6% global drift and 5.4% relative drift.

3.2.2 Effect of Exterior Finish

The responses of the three types of wet exterior finishes considered differed considerably. It would be expected that the stucco-only exterior finish would be the weakest, with the lowest drift capacity due to the stucco finish acting as a rigid body and only maintaining its connection to the framing through the furring nails, i.e., at lower displacement amplitudes, all of the imposed lateral load was transferred to the furring nails into the stucco. The furring nails had a 1/4-in. separation from the framing (spaced with a 1/4-in. wad at the head of the fastener); therefore, at lower displacements the stucco would detach from the furring nails as opposed to having a layer of sheathing between the stucco and the framing. When sheathing was present, the furring nails were driven through the sheathing into the studs. The furring nails were 1-1/2 in. in length, so their embedment in the framing was around 1/2 in. when sheathing was present (3/4 in. thickness of sheathing) and 1-1/4 in. when sheathing was not present.

As the cripple walls with sheathing displaced, the stucco and sheathing would effectively share imposed displacement instead of all of it being taken on by the stucco when sheathing was not present. This would lead to higher drift capacities for specimens with sheathing. In addition, the stiffness of the stucco-only cripple walls would be expected to be larger due to the rigid stucco taking all of the load, instead of both the stucco and the sheathing carrying the load. When diagonal sheathing is present, it would be expected that the stiffness would be high due to the orientation of the diagonal sheathing boards being better suited to resist lateral movement than the horizontal sheathing board spanning in the same direction as loading. The horizontal sheathing boards provide most of their resistance through the moment couple of the two fasteners attaching the boards the framing, whereas the diagonal sheathing—aided by the moment couple between the boards—are also able utilize their tensile and compressive strength as the cripple walls displace. This would inevitably lead to the stucco over diagonal sheathing boards to have the largest strength and drift capacity of any of the wet finishes, and the stucco over framing to have the lowest strength and drift capacity of any of the wet finishes. It would also be expected that the strength of the stucco-only versus the stucco over horizontal sheathing specimens would be similar due to the little amount of resistance that horizontal sheathing boards provide, while the drift capacity of the stucco over horizontal sheathing wall would be higher due to the separation that the sheathing provides between the stucco and the framing.

Analysis of the summary of lateral strength data for the existing specimens (Figure 3.33), the strongest cripple wall was finished with stucco over diagonal sheathing, with a lateral strength per linear foot of 1079 plf in the push direction and 975 plf in the pull direction. It should be noted that this asymmetry in lateral response was similarly observed for diagonally sheathed specimens tested in earlier phases of this program [Schiller et al. 2020(b)]. The average strength per linear foot between the two existing specimens with stucco over horizontal sheathing (Specimens A-20 and A-21) was 611 plf in the push direction and 566 plf in the pull direction, and for the stucco only specimens (Specimens A-17 and A-22), the average strength per linear foot was 545 plf in the push direction and 563 in the pull direction. Therefore, on average between both directions of loading, the stucco over diagonal sheathing finish provided a 75% increase in strength compared to the stucco over horizontal sheathing finish, and an 85% increase in the strength compared to the stucco only finish. The stucco over horizontal sheathing finish was 6% larger than the stucco-only finish. Although the responses are nonlinear, a superposition of finish elements would suggest that the diagonal sheathing provided over ten times the strength of the horizontal sheathing, as the added contribution of the horizontal sheathing increased the strength by 44 plf and the diagonal sheathing increased the strength by 473 plf. This analysis is based purely on subtracting the average strength of the stucco over sheathing specimens by the average strength of the stucco-only specimens. It should be noted that the stucco over diagonal sheathing specimen failed due to a cross-grain crack forming along the entire span of the cripple wall; therefore, had the sill plate and anchor bolts stayed intact, the strength would have been considerably higher, as the diagonal sheathing boards had not been fully mobilized.

A comparison of the relative drift ratios at strength is shown in Figure 3.35. On average for all existing 2-ft-tall specimens of the same finish type the average relative drift ratio at strength between both directions of loading was 1.3% for stucco-only cripple walls, 2.5% for stucco over horizontal sheathing cripple walls, and 2.3% for the stucco over diagonal sheathing cripple wall. The drift at strength would have been higher for the stucco over diagonal sheathing specimen had the cripple wall stayed intact.

To understand drift capacities of the cripple walls, there is value in measuring the relative drift at 80% pre-strength (Figure 3.37), relative drift at strength, and relative drift at 40% residual strength (Figure 3.38). On average for the stucco-only finished specimens the relative drift at 80% pre-strength was 0.5%, relative drift at strength was 1.3%, and relative drift a 40% residual strength was 3.7%, for a range of 3.2%. These values for the stucco over horizontal sheathing cripple walls were 1.2%, 2.5%, and 8.7%, for a range of 7.5%, and for the stucco over diagonal sheathing specimen were 1.2%, 2.3%, and 3.2%, for a range of 2%. For analysis of these values, the stucco over diagonal sheathing is not representative of the drift capacity of the cripple wall as large reductions in the relative drift occurred once cracks in the sill plates spread through the locations where the anchor bolts were located. This caused the relative displacement to decrease and subsequent increases in displacement amplitude as the imposed displacement was mostly taken by the sill plate displacing relative to the foundation. At 60% residual strength, the relative drift in the push direction of loading was 7.2% and 3.8% in the pull direction of loading (5.5% average between both directions). For this reason, the range is considered to be 4.4% (5.5–1.1%). As expected, the drift capacity of the stucco-only finished cripple walls was by far the lowest. The stucco over horizontal sheathing had the highest drift capacity.

The initial secant stiffness of the existing cripple walls is shown in Figure 3.39. The initial secant stiffness is defined as the secant stiffness associated with the relative drift at 80% pre-strength. The stucco-only finished specimens had the highest stiffness of 55.1 kip/in. on average between all specimens and both directions of loading. This was followed closely by the stucco over diagonal sheathing specimen, which had an average initial stiffness of 48.1 kip/in. The stucco over horizontal sheathing specimens were much more flexible, with an average initial stiffness of 25.7 kip/in. Therefore, the stucco-only finish was 114% stiffer than the stucco over horizontal sheathing finish and 15% stiffer than the stucco over diagonal sheathing specimen. In addition, the stucco over diagonal sheathing finish was 15% stiffer than the stucco over horizontal sheathing finish. These values followed expected trends.

3.2.3 Effect of Bottom Boundary Condition

Two boundary conditions for the bottom of the cripple walls were considered: bottom boundary condition “c” and “d”. Both bottom boundary condition “c” and “d” oriented the cripple wall so that all exterior finishes were outboard of foundation. This is the same whether there was a combined finish material or only the presence of a siding or stucco finish. Regardless of a single or combined finish material, the first layer of material attached to the framing was flush with the face of the footing.

Bottom boundary condition “d” pertained to cripple walls with a stucco-only or stucco over sheathing exterior finish. This boundary condition was similar to boundary condition “c”; however, the stucco was extended down the face of the footing by 8 in.; see Section 2.2. It should be noted that all cripple walls were constructed on a foundation exterior to the test loading rig so that batches of stucco-finished specimens could be constructed with similar materials and procedures, and then subsequently cured in place. Sequentially, individual specimens were then moved into the testing apparatus. During transportation of the specimens, the bond between the stucco extension and the foundation could easily detach, and it was observed that at least at the boundaries the stucco extensions had detached (for all cripple walls with bottom boundary condition “d”). This debonding made it difficult to concisely assess the contribution of the small extension of stucco to the lateral performance of the cripple walls; it is noted that given the likely vintage (> 50-years old since construction), the degrading of this region, near a home’s exterior hard- or soft-scape, might be anticipated.

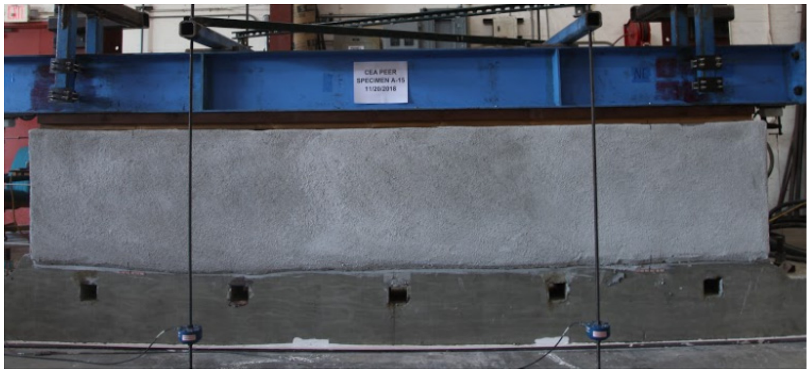
Two existing cripple walls were constructed with bottom boundary condition “d”: Specimen A-17, which was a stucco over framing finished specimen; and Specimen A-20, which was a stucco over horizontal sheathing finished specimen. Specimen A-22 was constructed with the same details as Specimen A-17 but with bottom boundary condition “c”. Specimen A-22 had an average lateral strength per linear foot of 551 in both directions of loading at 1.2% relative drift; Specimen A-17 had and average lateral strength per linear foot of 558 plf at 1.5% relative drift. Comparing the secant stiffness associated with relative drift at 80% pre-lateral strength, Specimen A-22 had an average initial stiffness of 57.7 kip/in., and Specimen A-17 had an average initial stiffness of 52.5 kip/in.

It would be expected that implementing bottom boundary condition “d” would provide a nominal increase to the stiffness and the strength of the cripple wall due to the additional length of bond between the stucco extension and the foundation. The results of the tests showed that neither the stiffness nor the strength increased in fact, they experienced a minor decrease. Absent specimen-to-specimen variability, this does point to the fact that the debonding was likely appreciable enough to lack facilitation of a robust comparison amongst bottom boundary condition “c” and “d”.

3.2.4 Effect of Wet Set Sill

Specimen A-21 was constructed with the same details as Specimen A-20, with the exception of their differences in anchorage and bottom boundary condition. Specimen A-21 was an existing 2-ft-tall cripple wall with stucco over horizontal sheathing and bottom boundary condition "c"; Specimen A-20 had a typical anchorage with a sill plate fastened by three anchor bolts spaced at 64 in. on center and bottom boundary condition "d". As discussed previously, the change in the bottom boundary condition had little effect on the response of the specimen and comparisons between the two specimens can be made. The lateral strength per linear foot of the wet set sill specimen was 624 plf in the push direction and 592 plf in the pull direction. For the typical sill plate specimen, the lateral strength per linear foot of the wet set sill specimen was 598 plf in the push direction and 539 plf in the pull direction. Implementation of the wet set sill provided a 7% increase in the strength of the cripple wall. The relative drift at strength was nearly identical for both specimens—on average 2.5% drift for the wet set sill specimen and 2.4% for the typical sill plate specimen however, the drift capacity increased for the wet set sill specimen. The relative drift at 80% pre-strength of the wet set sill specimen was on average 1.1% and at 40% residual strength was 9.7%, for a range of 8.6%. For the typical sill plate specimen, these values were 1.4% and 7.7%, for a range of 6.3%. When a monotonic push was initiated for the wet set sill specimen after an 80% drop in strength, the cripple wall exhibited a significant increase in strength, which was not observed with the typical sill plate specimen.

This increase in strength was due to all gaps between the sheathing boards closing, which caused the sheathing boards to bear on one another. This bearing of the sheathing allowed the sheathing boards to provide more lateral resistance than before when the gaps were present. Most of the lateral resistance can be attributed to the moment couple between the fasteners attaching the sheathing to the framing. The typical sill plate specimen did not have a drop in load from the monotonic push, but it did not increase from the previous drift ratio cycle, showing that the sheathing boards had not been mobilized to the same degree as the wet set sill specimen. The largest difference in response between the two cripple walls was the change in initial stiffness. The initial secant stiffness for the wet set sill specimen was 29.7 kip/in on average, and for the typical sill plate specimen, it was 21.8 kip/in., showing that the installation of the wet set sill plate produced a 36% increase in stiffness to the specimen.



(a)

(b)

(c)

(d)

Figure 3.1 **Specimen A-15 pre-test photographs of the existing 2-ft-tall cripple wall with stucco over diagonal sheathing exterior finish and bottom boundary condition "c": (a) exterior elevation; (b) interior elevation; (c) north interior corner; and (d) north exterior corner.**

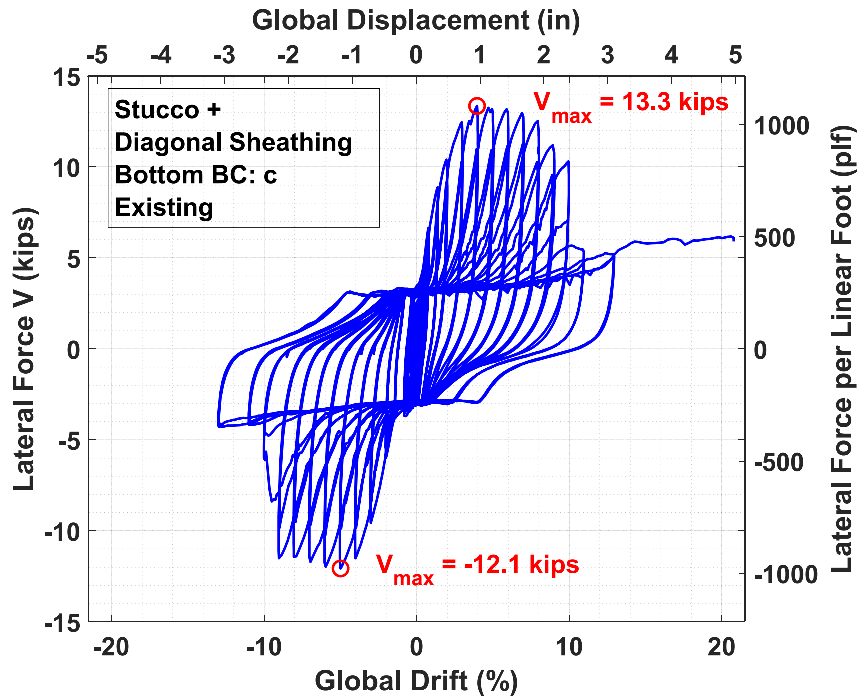


Figure 3.2 **Specimen A-15 lateral force versus *global* lateral drift and displacement hysteresis.**

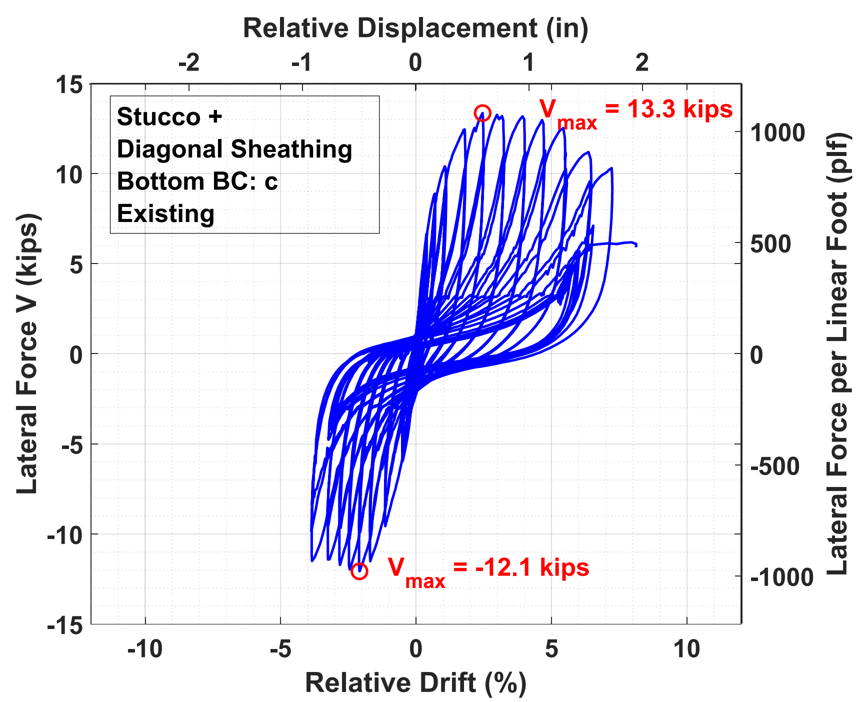


Figure 3.3 **Specimen A-15 lateral force versus *relative* lateral drift and displacement hysteresis.**

(a)

(b)

(c)

(d)

Figure 3.4 Specimen A-16 pre-test photographs of the retrofitted 2-ft-tall cripple wall with stucco over diagonal sheathing exterior finish and bottom boundary condition "c": (a) exterior elevation; (b) interior elevation; (c) south interior corner; and (d) north exterior corner.

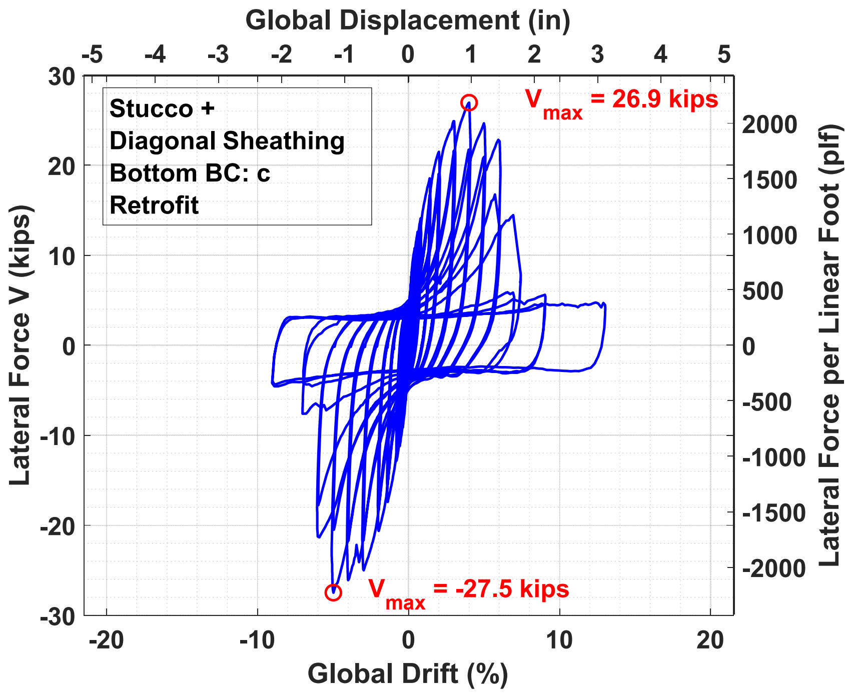


Figure 3.5 Specimen A-16 lateral force versus *global* lateral drift and displacement hysteresis.

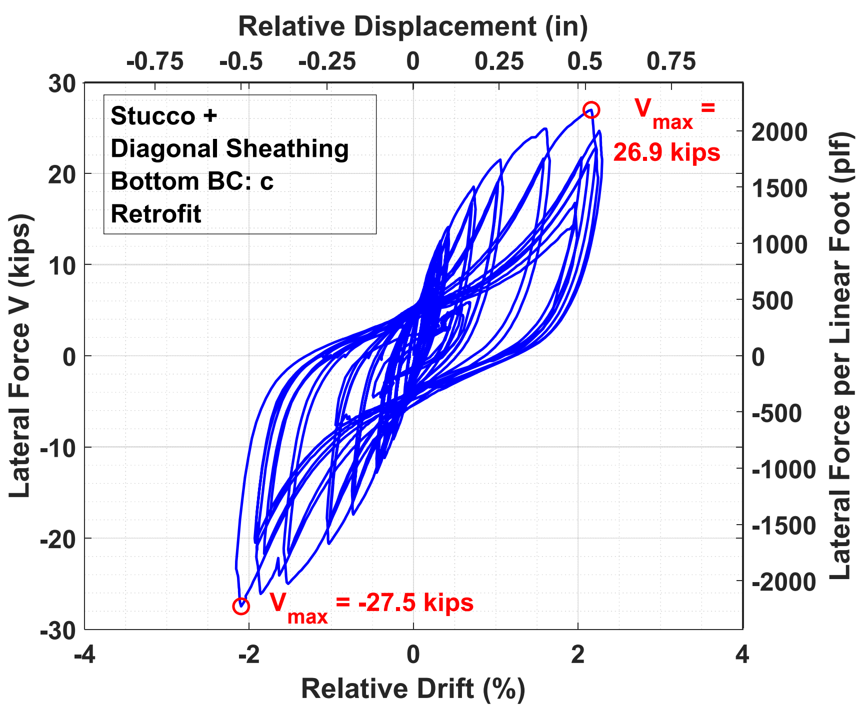
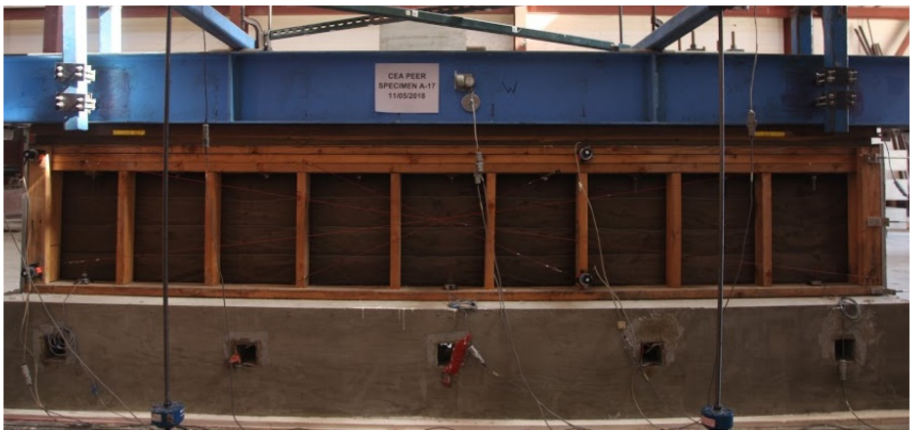


Figure 3.6 Specimen A-16 lateral force versus *relative* lateral drift and displacement hysteresis.

(a)



(b)

(c)

(d)

Figure 3.7 **Specimen A-17 pre-test photographs of the existing 2-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition "d": (a) exterior elevation; (b) interior elevation; (c) south interior corner; and (d) south exterior corner.**

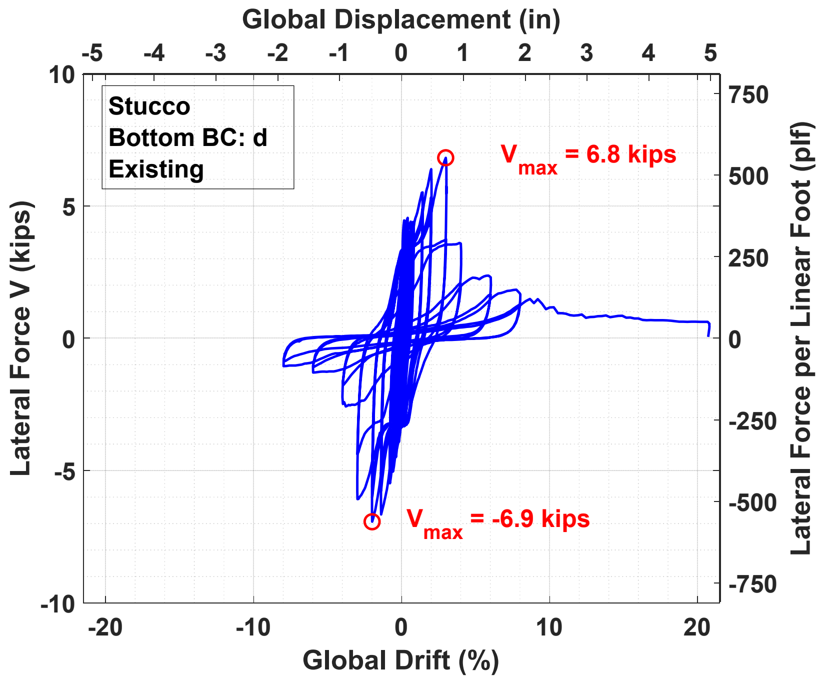


Figure 3.8 Specimen A-17 lateral force versus *global* lateral drift and displacement hysteresis.

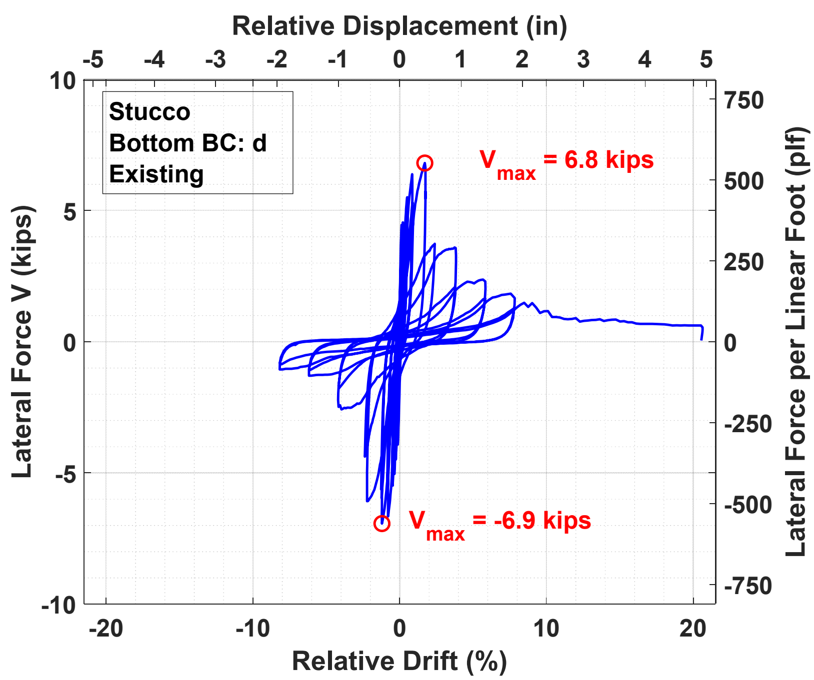


Figure 3.9 Specimen A-17 lateral force versus *relative* lateral drift and displacement hysteresis.

(a)

(b)

(c)

(d)

Figure 3.10 Specimen A-18 pre-test photographs of the retrofitted 2-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition “d”: (a) exterior elevation; (b) interior elevation; (c) south interior corner; and (d) south exterior corner.

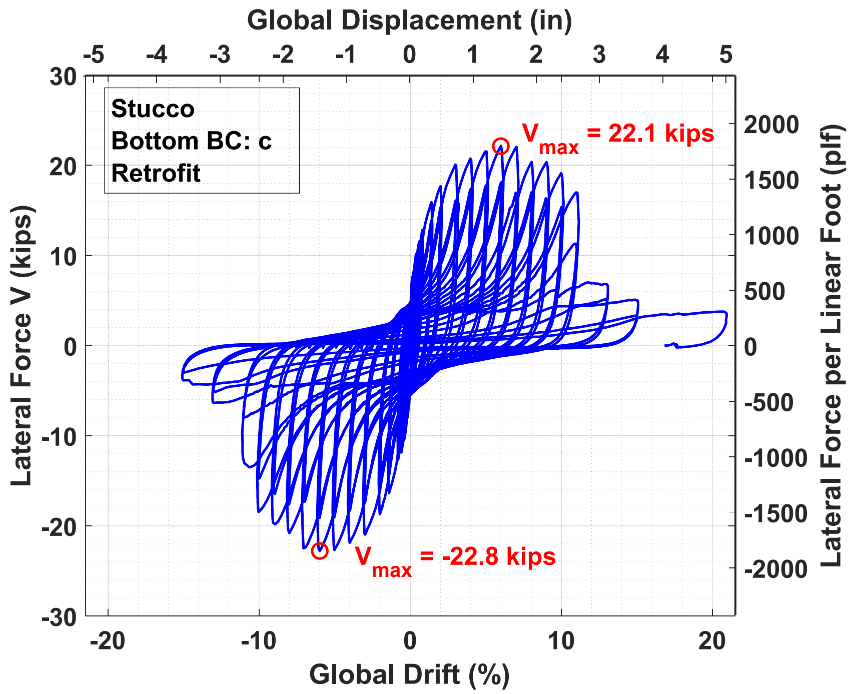


Figure 3.11 **Specimen A-18 lateral force versus *global* lateral drift and displacement hysteresis.**

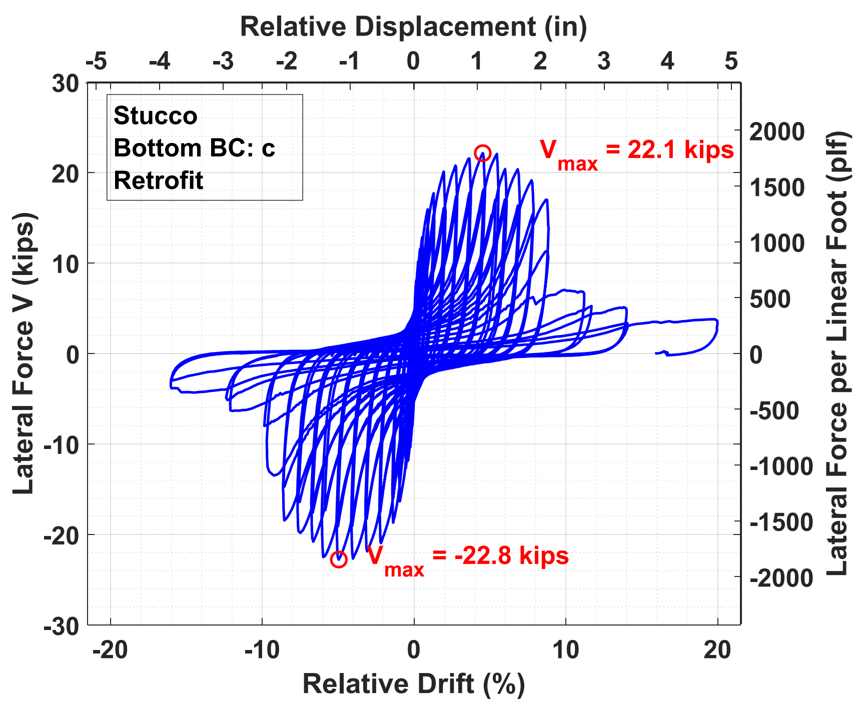
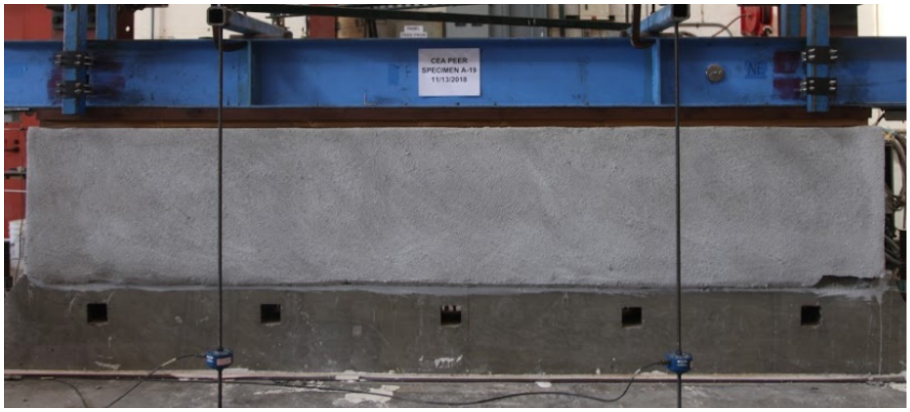
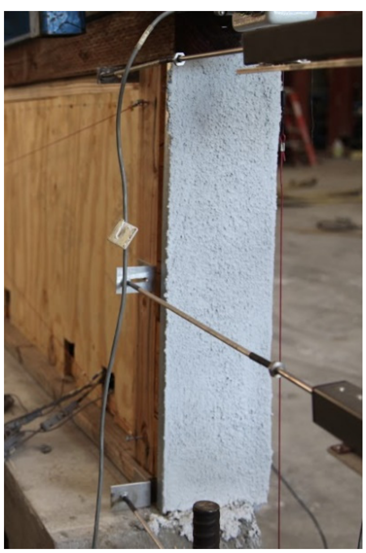


Figure 3.12 **Specimen A-18 lateral force versus *relative* lateral drift and displacement hysteresis.**



(a)

(b)



(c)

(d)

Figure 3.13 Specimen A-19 pre-test photographs of the retrofitted 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish and bottom boundary condition "c": (a) exterior elevation; (b) interior elevation; (c) south interior corner; and (d) south exterior corner.

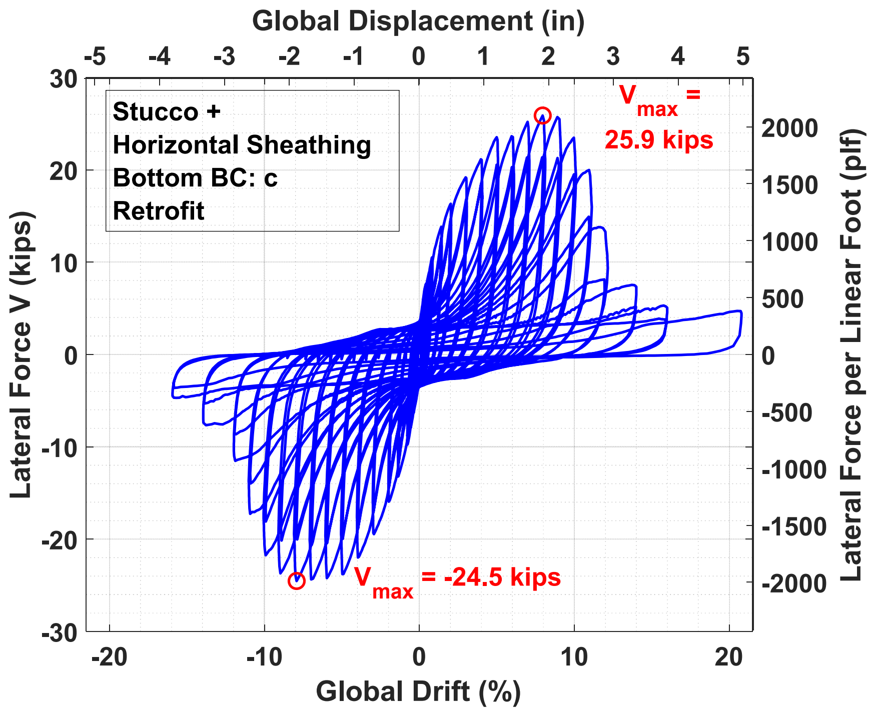


Figure 3.14 Specimen A-19 lateral force versus *global* lateral drift and displacement hysteresis.

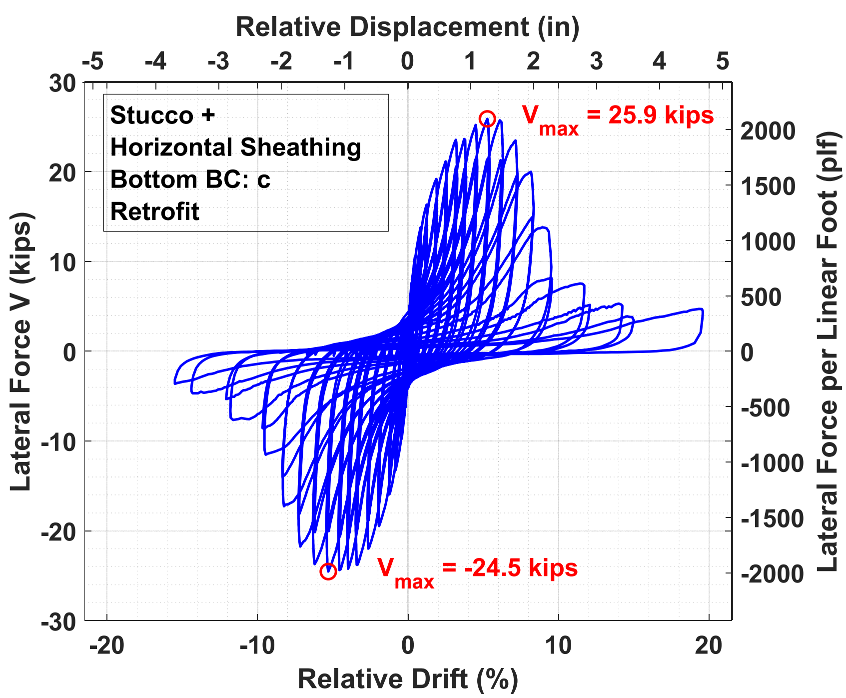


Figure 3.15 Specimen A-19 lateral force versus *relative* lateral drift and displacement hysteresis.

(a)

(b)

(c)

(d)

Figure 3.16 Specimen A-20 pre-test photographs of the existing 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish and bottom boundary condition “d”: (a) exterior elevation; (b) interior elevation; (c) south interior corner; and (d) north corner end.

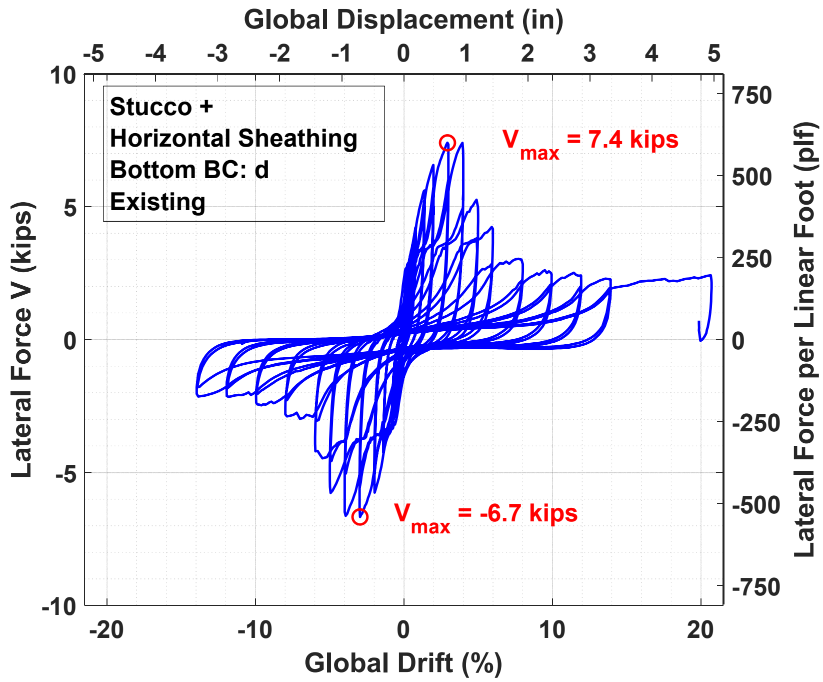


Figure 3.17 **Specimen A-20 lateral force versus *global* lateral drift and displacement hysteresis.**

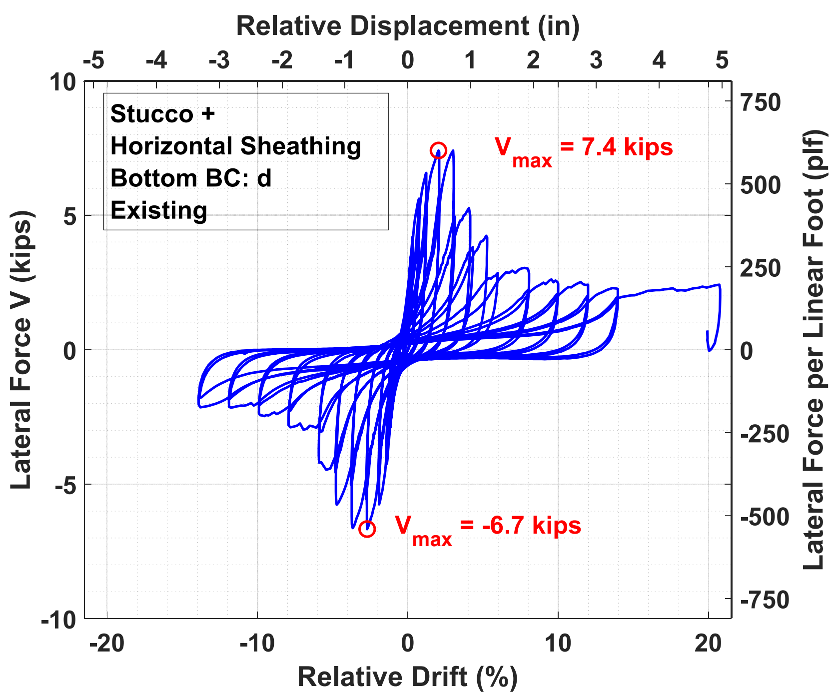
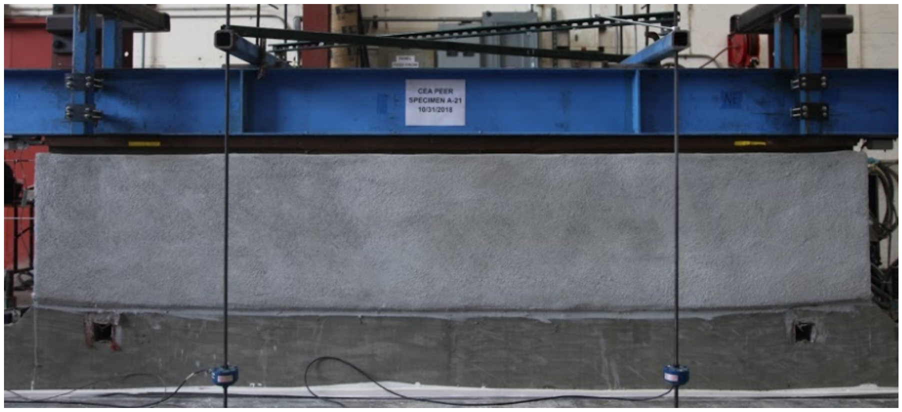


Figure 3.18 **Specimen A-20 lateral force versus *relative* lateral drift and displacement hysteresis.**



(a)

(b)

(c)

(d)

Figure 3.19 Specimen A-21 pre-test photographs of the existing 2-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition "c" with wet set sill plate: (a) exterior elevation; (b) interior elevation; (c) south interior corner; and (d) north exterior corner.

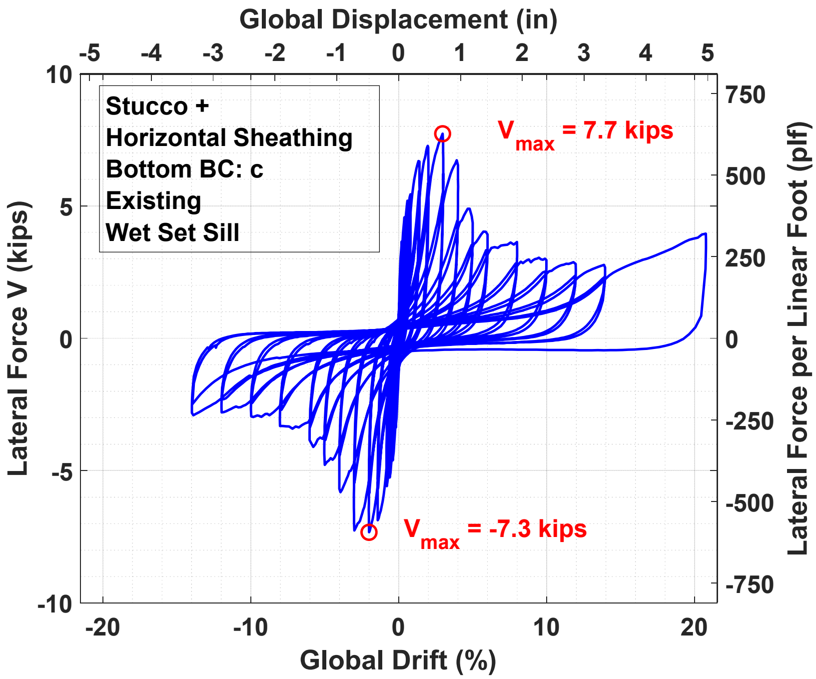


Figure 3.20 Specimen A-21 lateral force versus *global* lateral drift and displacement hysteresis; there was no difference between the global response and the relative response.

(a)

(b)

(c)

(d)

Figure 3.21 Specimen A-22 pre-test photographs of the existing 2-ft-tall cripple wall with stucco exterior finish and bottom boundary condition “c”: (a) exterior elevation; (b) interior elevation; (c) north exterior corner; and (d) south interior corner.

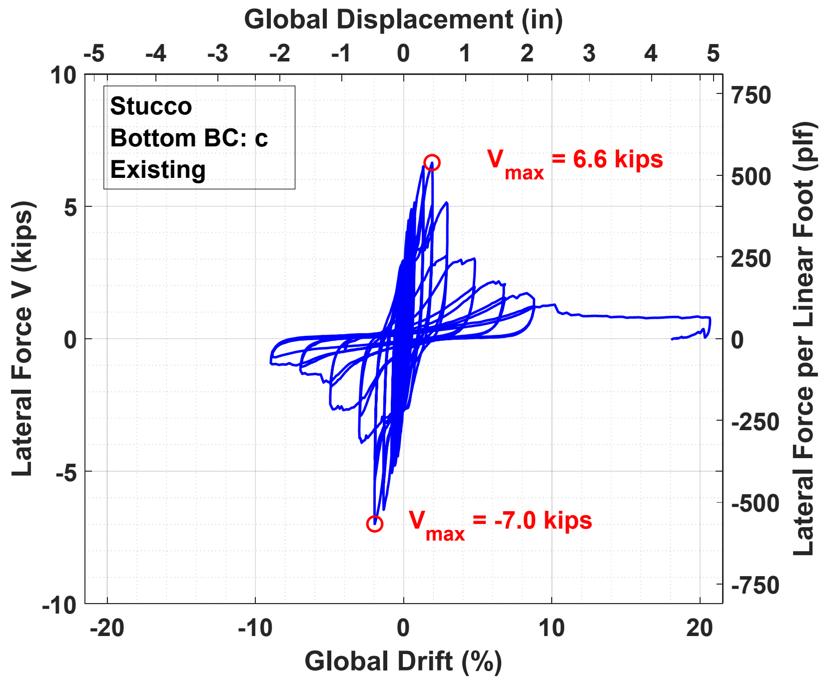


Figure 3.22 **Specimen A-22 lateral force versus *global* lateral drift and displacement hysteresis.**

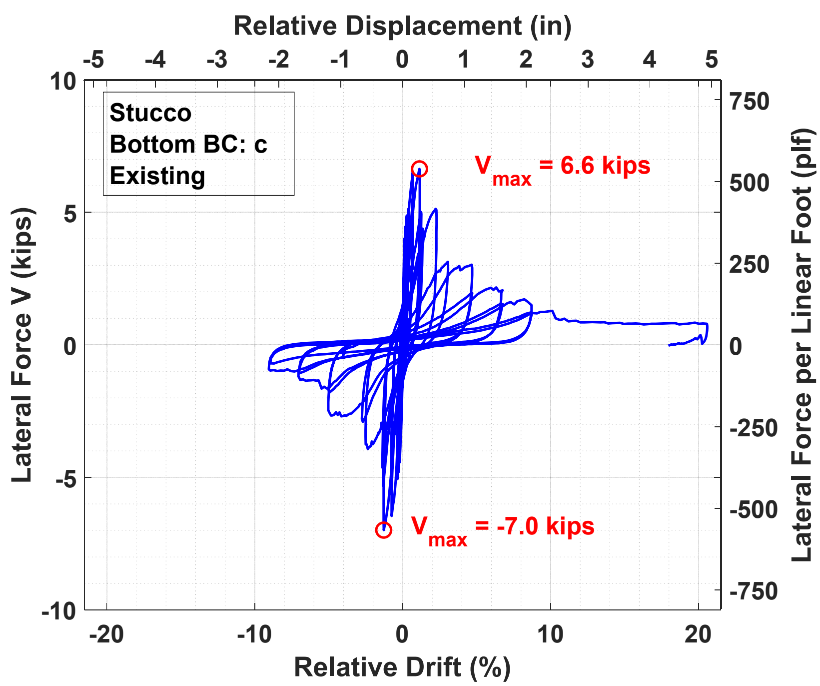


Figure 3.23 **Specimen A-22 lateral force versus *relative* lateral drift and displacement hysteresis.**

(a)

(b)

Figure 3.24 **Specimen A-25 pre-test photographs of the existing 6-ft-tall cripple wall with stucco exterior finish and bottom boundary condition "c": (a) exterior elevation; (b) interior elevation; (c) north interior corner; and (d) north exterior corner.**

(c) (d)

Figure 3.24 (continued).

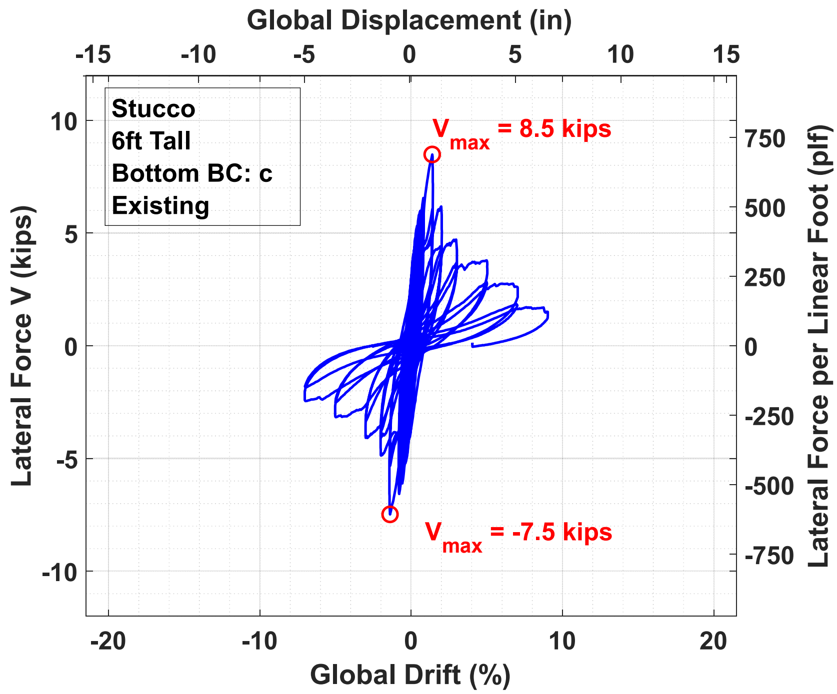


Figure 3.25 Specimen A-25 lateral force versus *global* lateral drift and displacement hysteresis.

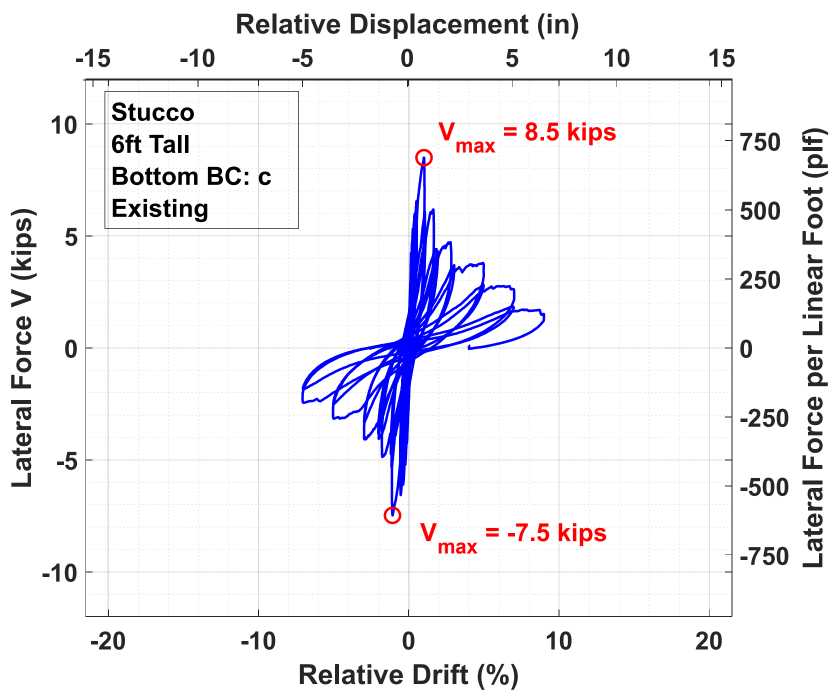
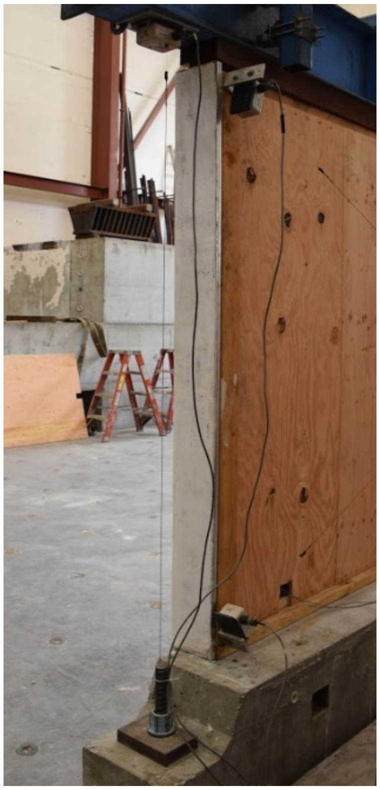


Figure 3.26 Specimen A-25 lateral force versus *relative* lateral drift and displacement hysteresis.

(a)

(b)

Figure 3.27 Specimen A-26 pre-test photographs of the retrofitted 6-ft-tall cripple wall with stucco exterior finish and bottom boundary condition "c": (a) exterior elevation; (b) interior elevation; (c) north interior end; and (d) south exterior corner.



(c)

(d)

Figure 3.27 (continued).

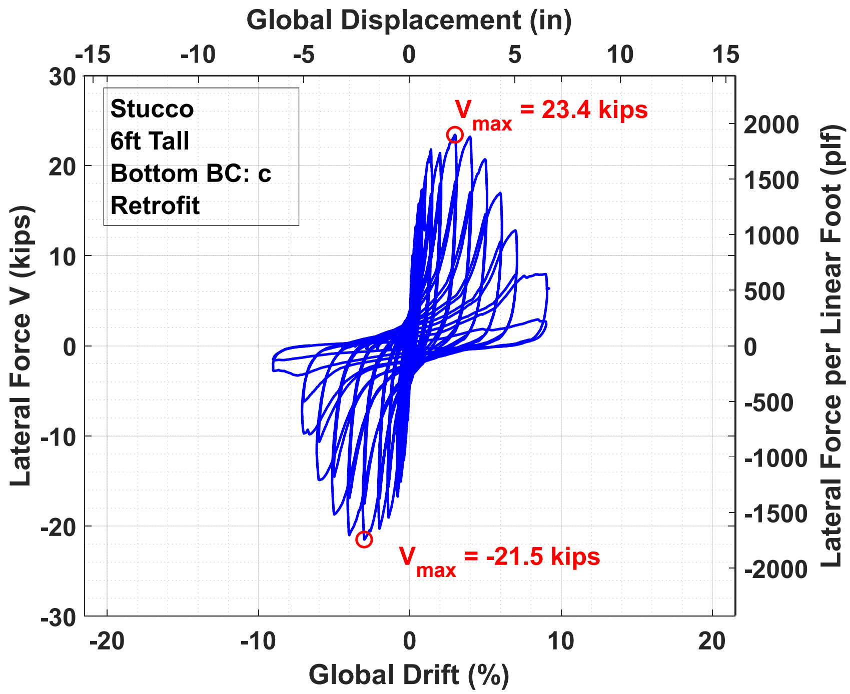


Figure 3.28 Specimen A-26 lateral force versus *global* lateral drift and displacement hysteresis.

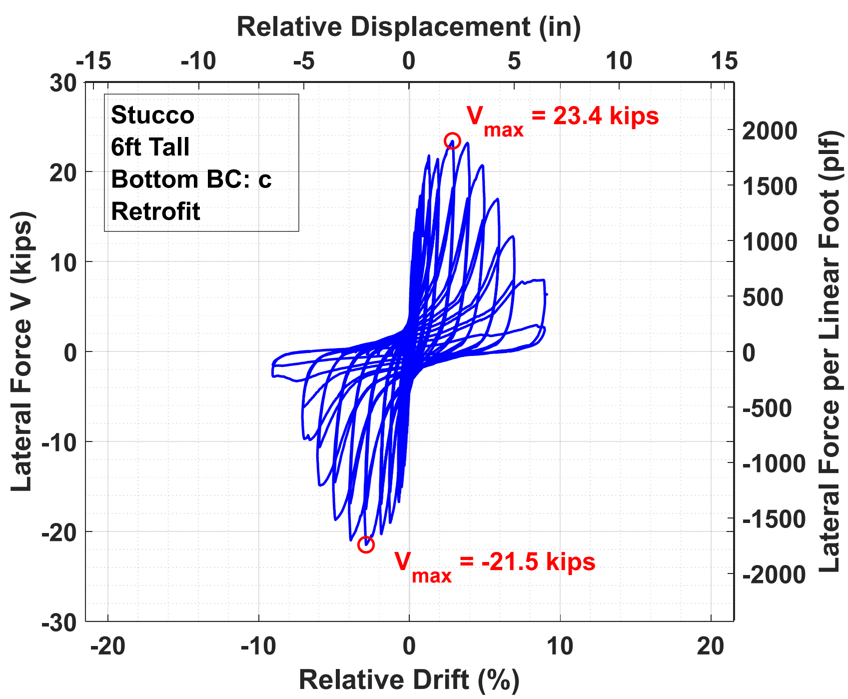
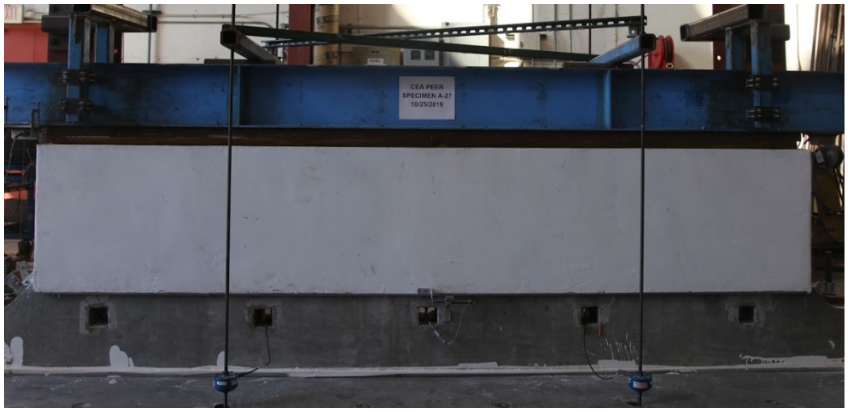
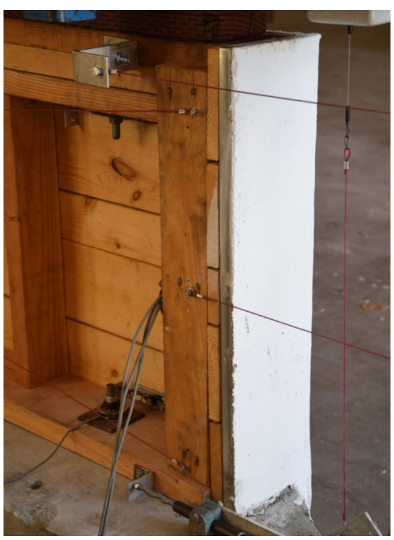


Figure 3.29 Specimen A-26 lateral force versus *relative* lateral drift and displacement hysteresis.



(a)

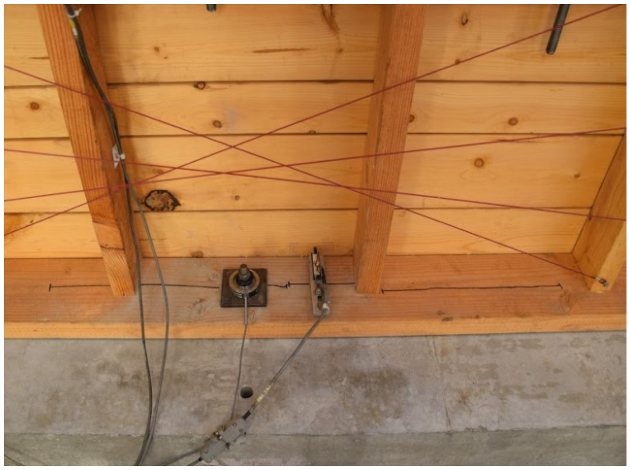
(b)



(c)

(d)

Figure 3.30 Specimen A-27 pre-test photographs of the existing 2-ft-tall cripple wall with stucco exterior finish and bottom boundary condition "c" with monotonic push loading: (a) exterior elevation; (b) interior elevation; (c) south interior corner; (d) south exterior corner; and (e) sill plate cracks in middle interior.



(e)
Figure 3.30 (continued).

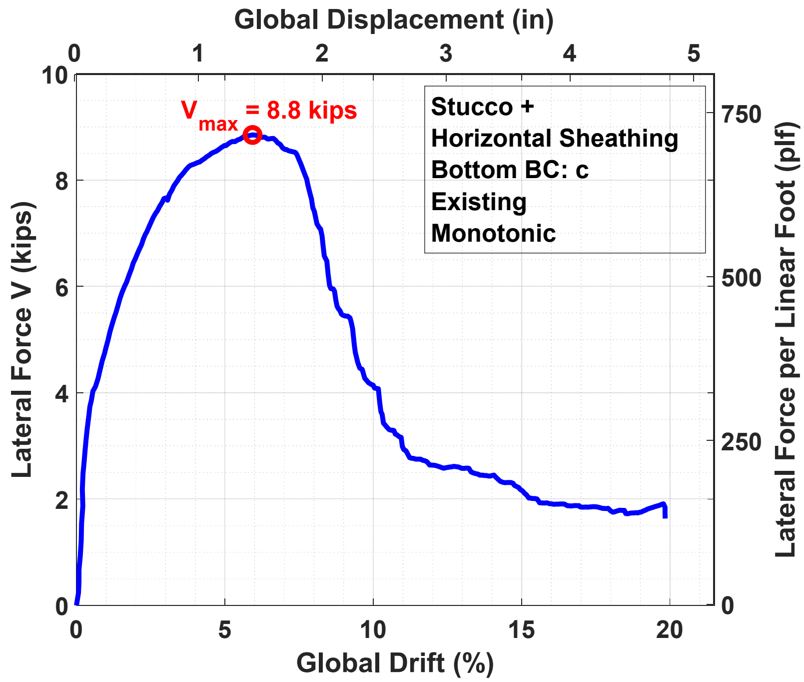


Figure 3.31 Specimen A-27 lateral force versus *global* lateral drift and displacement response. Note: specimen tested under monotonic loading.

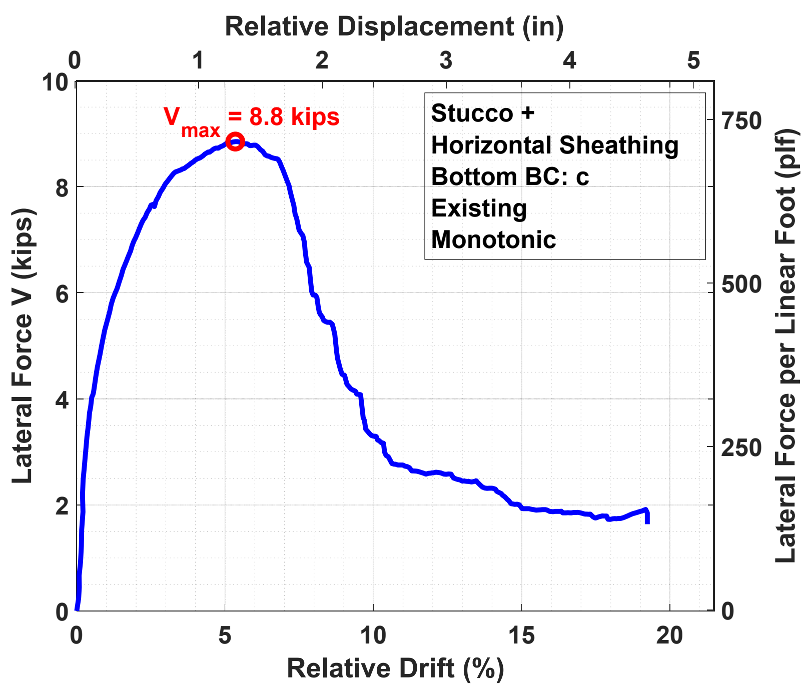


Figure 3.32 Specimen A-27 lateral force versus *relative* lateral drift and displacement response.

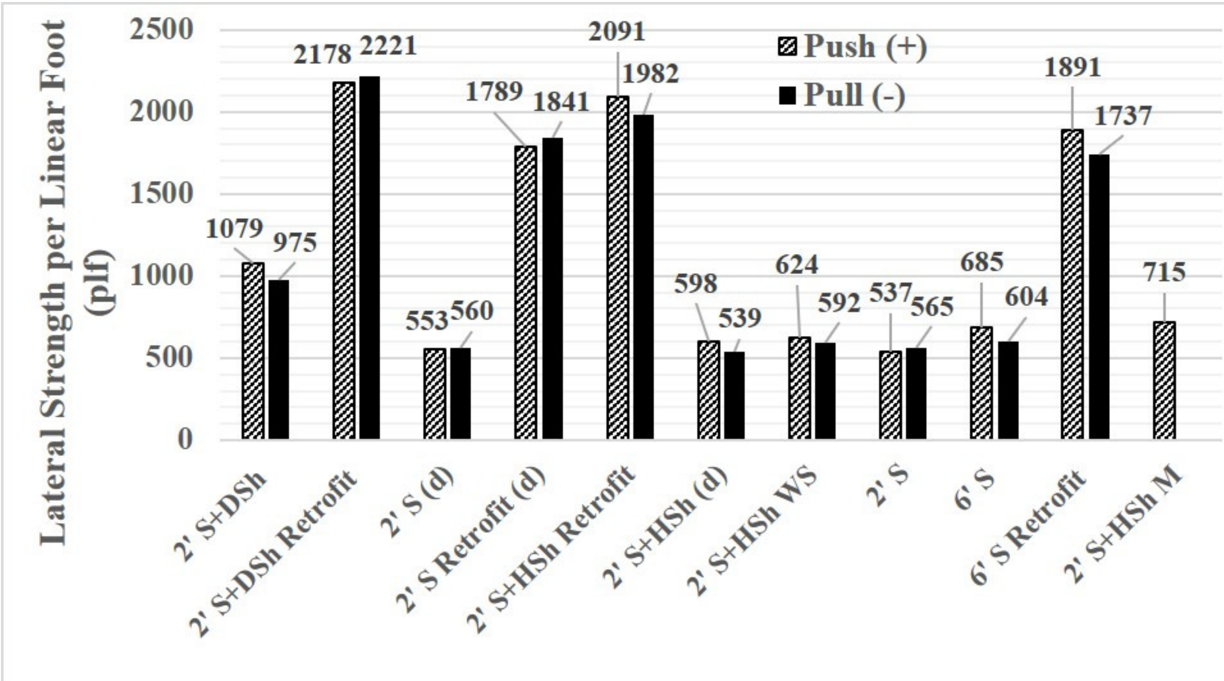


Figure 3.33 Comparison of lateral strength per linear foot of cripple walls.

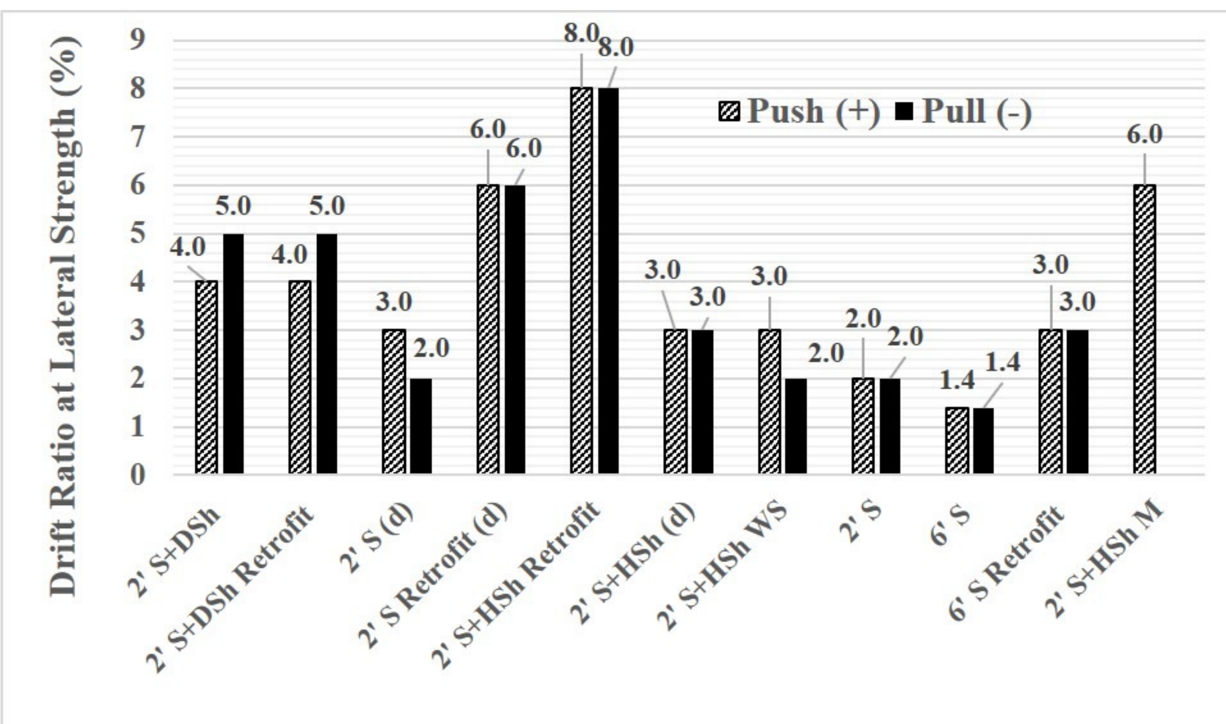


Figure 3.34 Comparison of *global* drift at lateral strength.

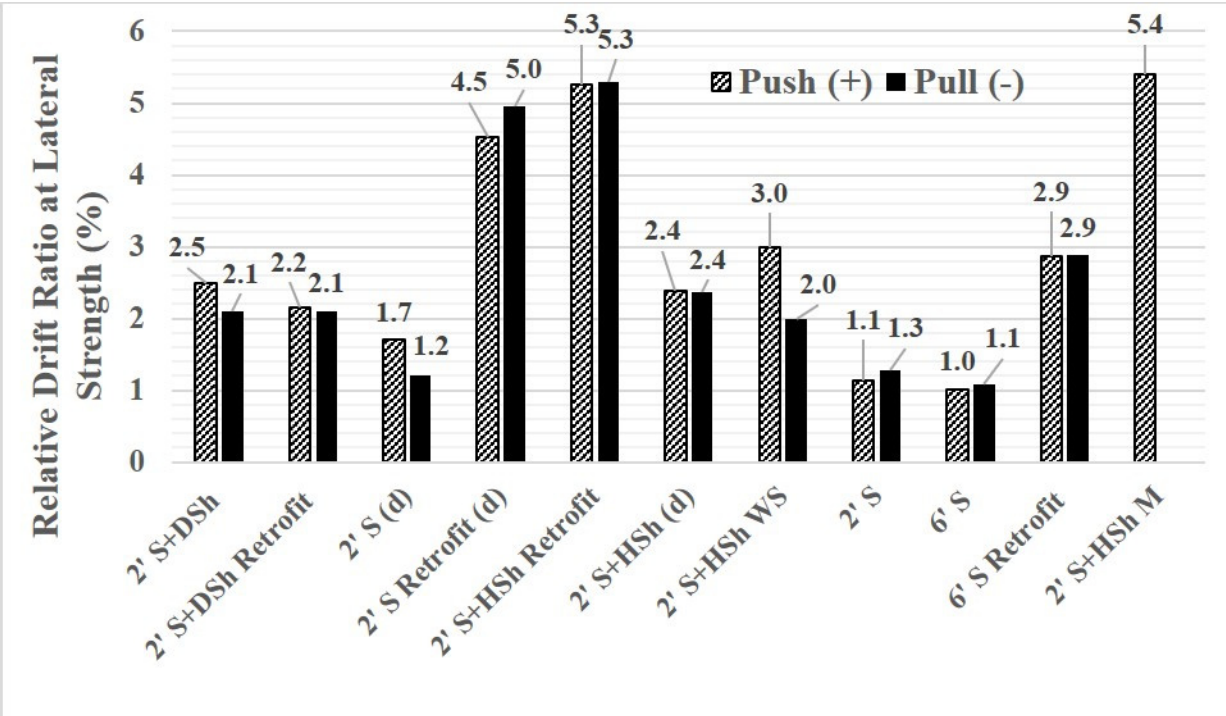


Figure 3.35 Comparison of *relative* drift at lateral strength.

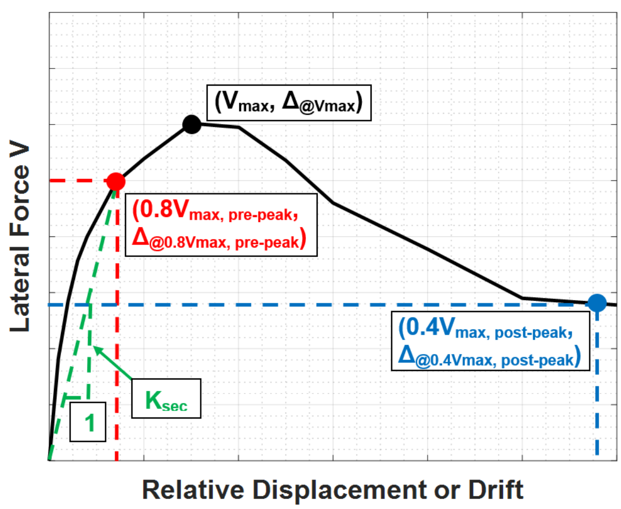


Figure 3.36 Schematic defining key parameters cross-compared amongst specimens in report: initial secant stiffness, relative drift at 80% lateral strength (pre-strength), and relative drift at 40% lateral strength (post-strength) from an envelope of the response.

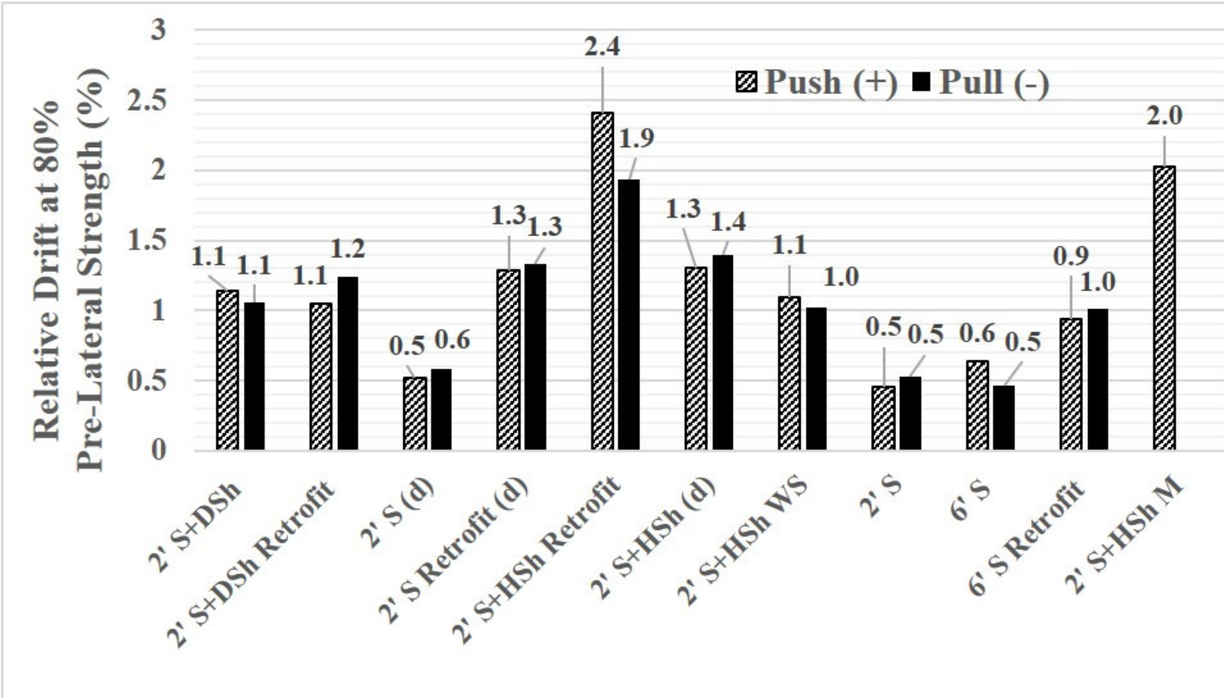


Figure 3.37 Comparison of *relative* drift at 80% lateral strength, pre-lateral strength (0.8 V_{max}).

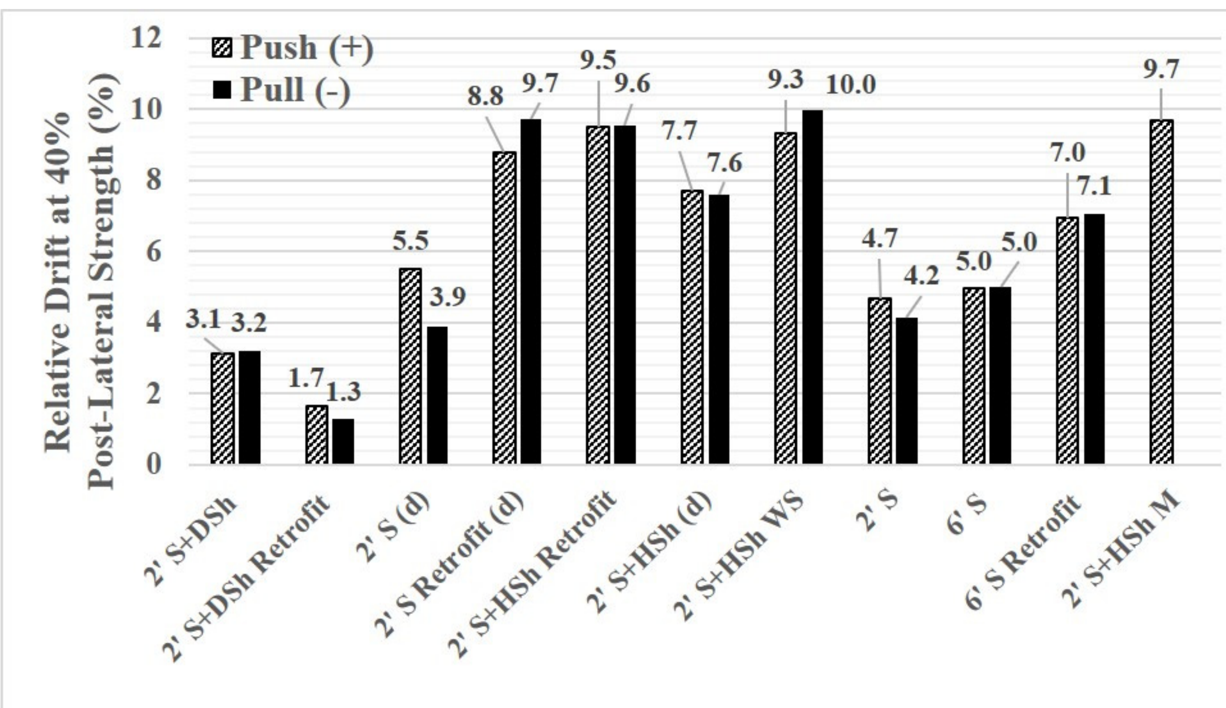


Figure 3.38 Comparison of *relative* drift at 40% lateral strength, post-lateral strength (0.4 V_{max}).

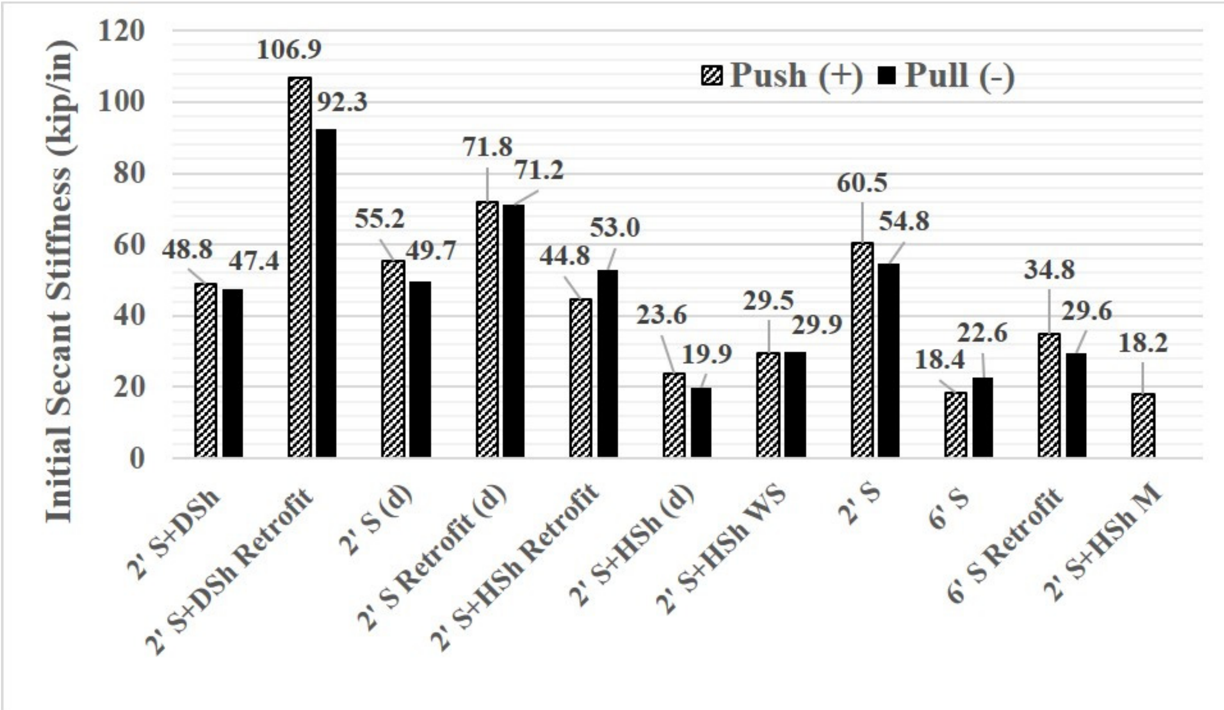


Figure 3.39 Secant stiffness for *relative* drift at 80% pre-lateral strength.

3.3 SILL PLATE DISPLACEMENT RELATIVE TO FOUNDATION

It is important to characterize the contribution of the lateral displacement of the walls from various components. One such potentially significant contributor is the displacement of the sill plate relative to the foundation. As shown in figures in Section 3.2, often the global response—including the combined sliding of the sill plate and displacement of the cripple wall structure—dramatically differs from the relative response, i.e., the displacement of the cripple wall structure only. For all cripple walls tested, the anchor bolt holes were oversized by 1/4 in. This is a common construction practice in California wood-frame construction as it alleviates the precision needed to frame walls, leading to quicker construction that is prone to fewer mistakes. The exception to this practice was the addition of the anchor bolts per the *FEMA P-1100* prescriptive retrofit. Many of these anchor bolts were embedded into the foundation and epoxied into place. For all anchor bolts in this category, the anchor holes were only oversized by 1/16 in. Because the anchor bolt holes were oversized, there was less resistance to sliding of the sill plate on the foundation, as the anchor bolts will not immediately be working to resist the sliding. The resistance to this sliding will initially come from the frictional resistance between the bottom of the sill plate and the top of the foundation. Through a static analysis, the initiation of sliding can be estimated if the normal force provided by the weight of the cripple wall and the imposed vertical load and the coefficient of friction between wood and concrete is known, as will be discussed in Section 3.3.1. It should be noted, however, that the concrete footings are finished using a smooth steel trowel, which may not necessarily emulate older construction practices.

Figure 3.40 through 3.59 describe the displacement of the sill plate relative to the foundation. Even-numbered figures compare the global drift/displacement versus the sill relative drift/displacement. Odd-numbered figures compare the lateral force versus the sill relative drift/displacement. Specimen A-21, an existing 2-ft-tall specimen with stucco over horizontal sheathing exterior finish and a wet set sill plate, did not have any movement of the sill plate during testing due to its anchorage condition; therefore, it is not considered here.

Since the wet set sill plate is embedded in the concrete during the pouring of the foundation and contains 30 penny nails (6-in. nails) along the sill plate (which are also embedded into the concrete), there is a much higher resistance to sliding than the frictional resistance between the sill plate and the concrete foundation. All specimens underwent considerable displacements of the sill plate relative to the foundation during loading. As a general trend for all specimens, the higher the lateral strength of the cripple wall, the larger the displacement between the sill plate and the foundation was. Therefore, the retrofitted specimens exhibited the largest displacements of the sill plate relative to the foundation. The exception to this trend was Specimen A-26, the retrofitted 6-ft-tall specimen with stucco exterior finish. The sill plate relative drift was less than 0.15% in both directions, which was the lowest value by a large margin. There was a much higher resistance to sliding due to the four of the anchor bolts for this specimen embedded into the foundation and epoxied as well as tie-downs being installed on both ends of the cripple wall. Specimen A-25, its existing counterpart also experienced little movement of the sill plate on the foundation, on average 0.26 in., which is less than 0.4% of sill relative drift. This is a result of the strength of the cripple wall being relatively low compared with the other specimens and the height of the cripple wall. Taller walls have a tendency for more uplift and less sliding as the response is more flexure dominated than shear dominated compared to shorter cripple walls.

All cripple walls underwent displacement of the sill plate that increased as the lateral load increased. In all cases, the sill plate's displacement relative to the foundation was greater in the pull direction than the push direction. This is due to the cripple walls initially being loaded in the push direction. On average for the existing 2-ft-tall specimens, the average sill plate to foundation displacement was 0.24 in. (1.0% relative drift) in the push direction and 0.14 in. (0.6% relative drift) in the pull direction. For the retrofitted 2-ft-tall specimens, the average sill plate to foundation displacement increased to 0.62 in. (2.6% relative drift) in the push direction and 0.51 in. (2.1% relative drift) in the pull direction. These values exclude the stucco over diagonal sheathing finish specimens, which experienced the largest sill relative displacements due to anchor bolt fractures and sill plate cracks. By the end of the tests, around 90% of the imposed displacement was constituted in the form of displacement of the sill plate relative to the foundation.

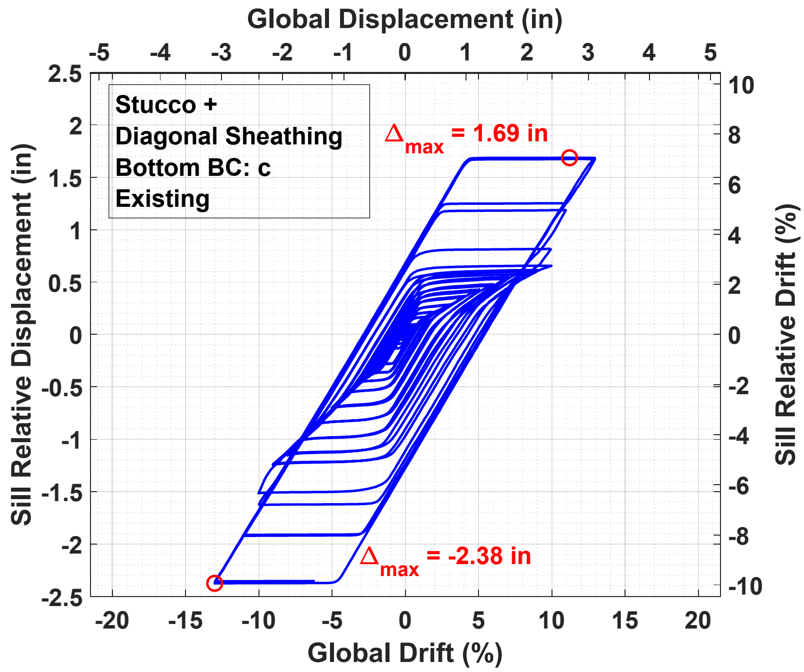


Figure 3.40 **Specimen A-15 sill plate to foundation relative displacement versus *global* drift.**

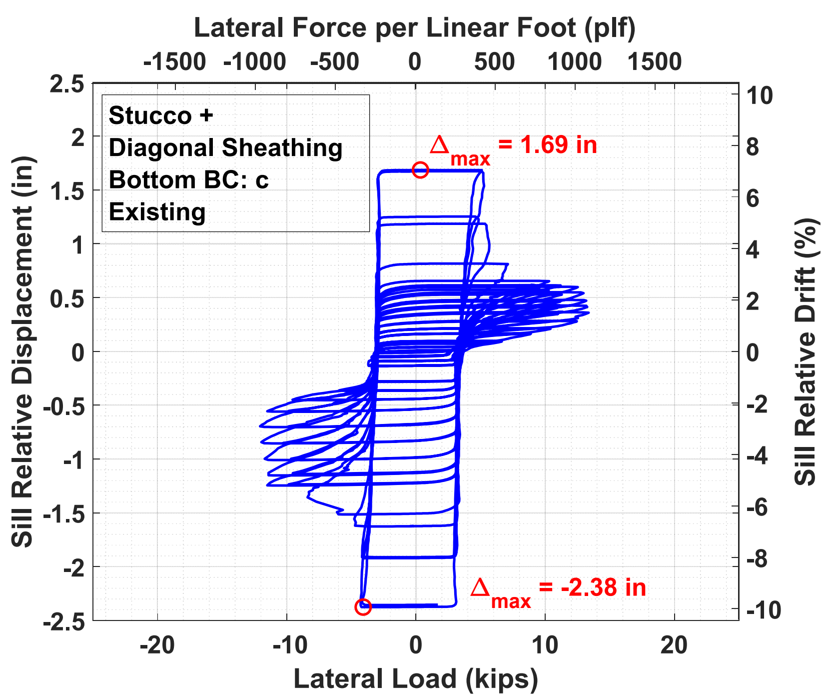


Figure 3.41 **Specimen A-15 sill plate to foundation relative displacement versus lateral strength.**

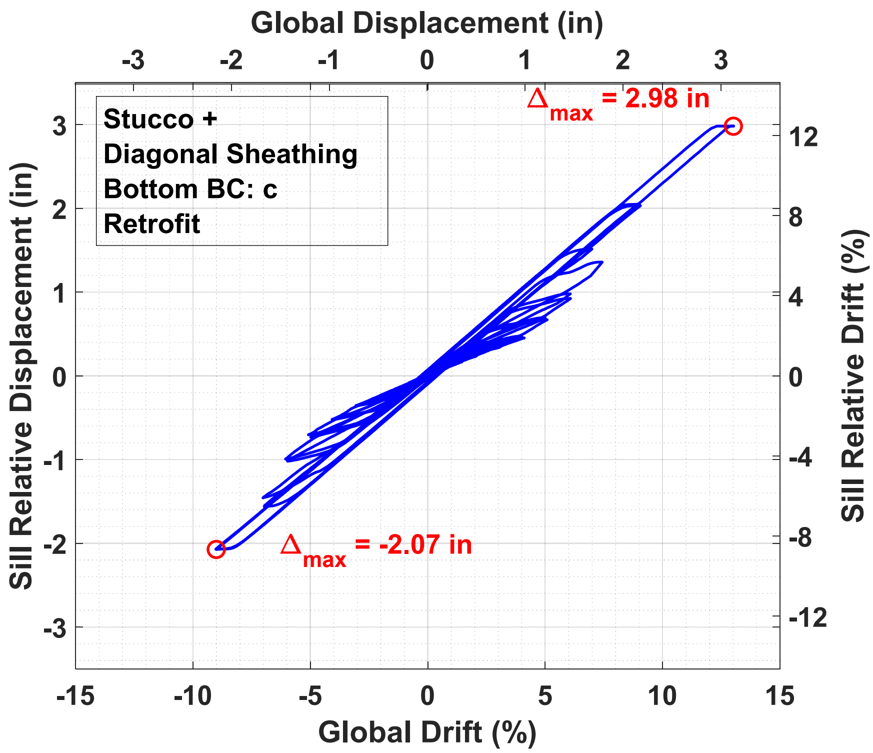


Figure 3.42 Specimen A-16 sill plate to foundation relative displacement versus *global* drift.

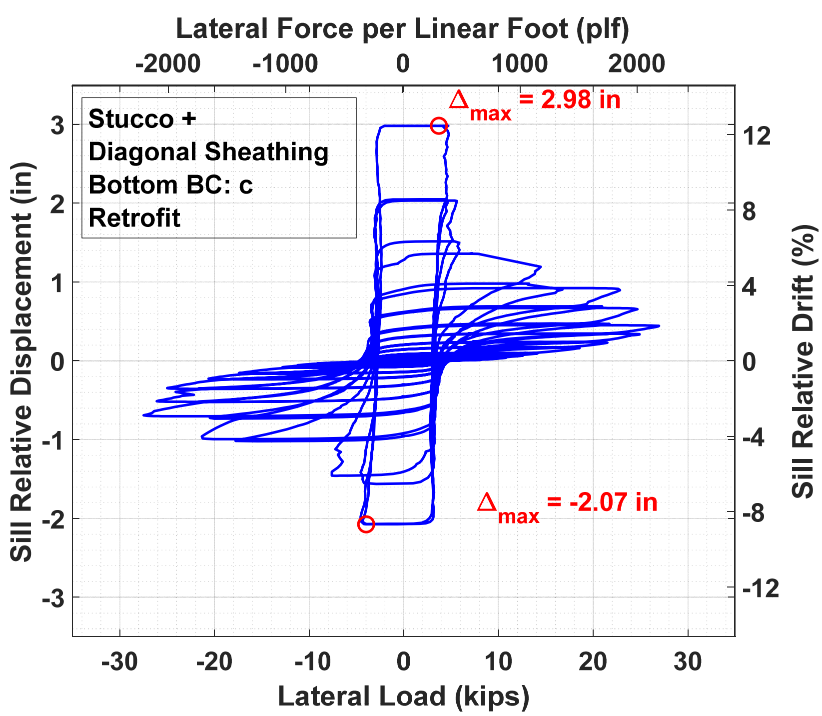


Figure 3.43 Specimen A-16 sill plate to foundation relative displacement versus lateral strength.

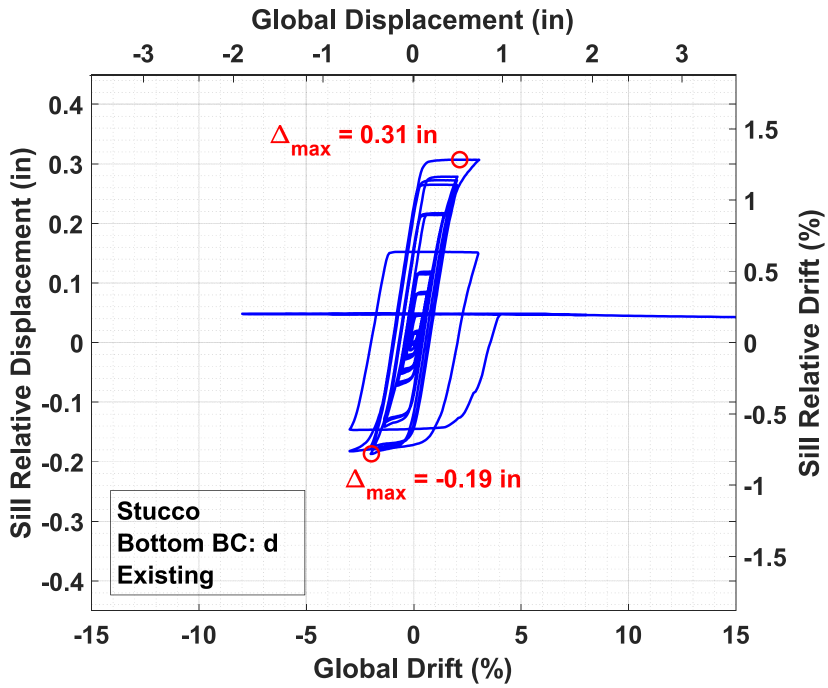


Figure 3.44 Specimen A-17 sill plate to foundation relative displacement versus *global* drift.

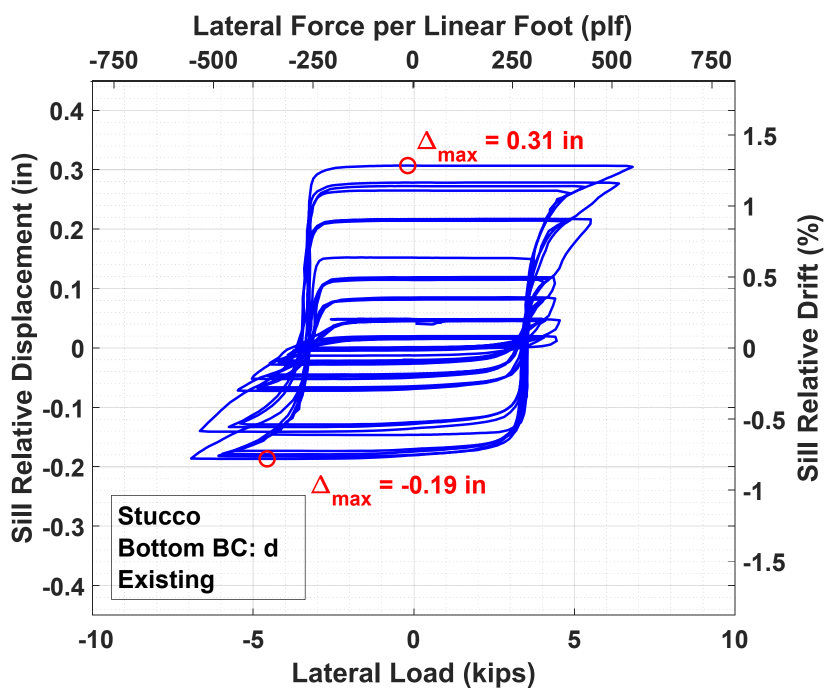


Figure 3.45 Specimen A-17 sill plate to foundation relative displacement versus lateral strength.

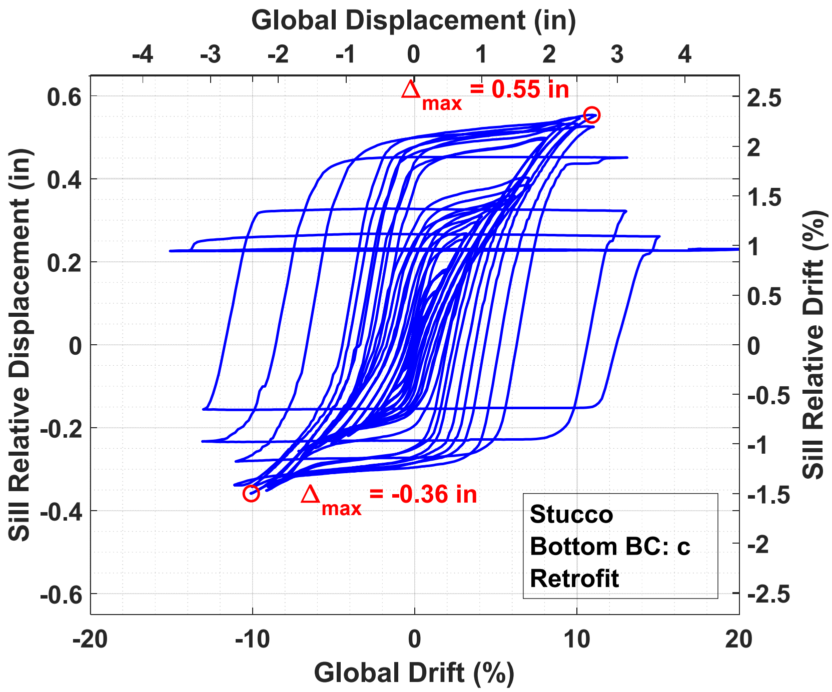


Figure 3.46 Specimen A-18 sill plate to foundation relative displacement versus ***global*** drift.

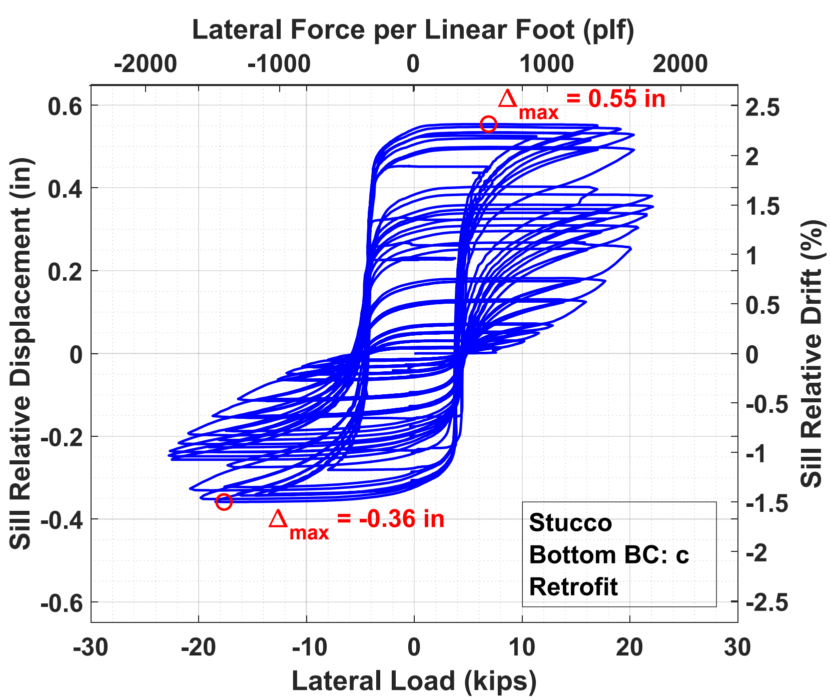


Figure 3.47 Specimen A-18 sill plate to foundation relative displacement versus lateral strength.

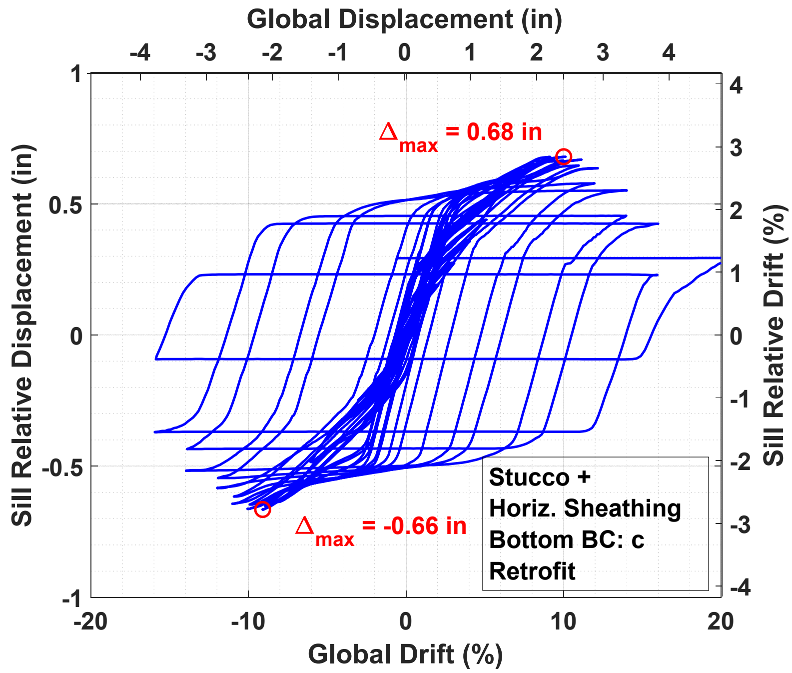


Figure 3.48 Specimen A-19 sill plate to foundation relative displacement versus *global* drift.

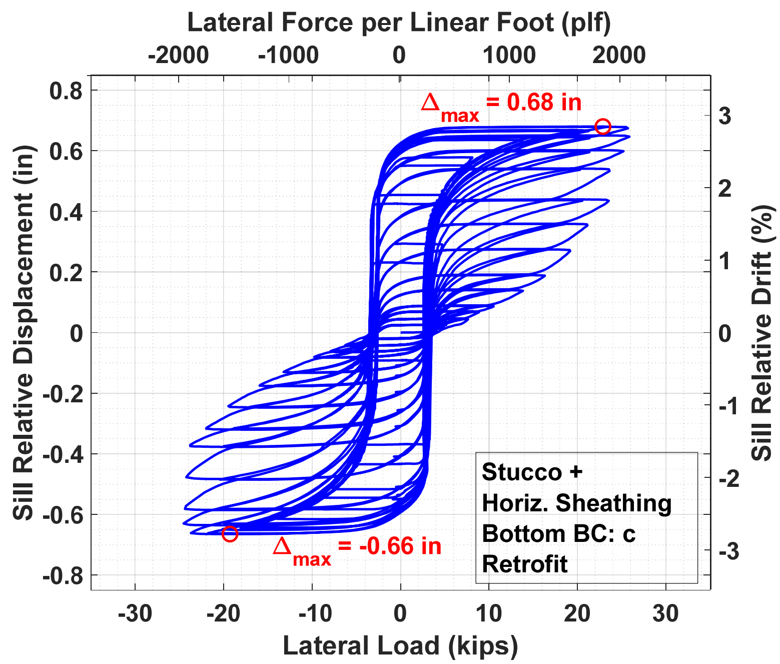


Figure 3.49 Specimen A-19 sill plate to foundation relative displacement versus lateral strength.

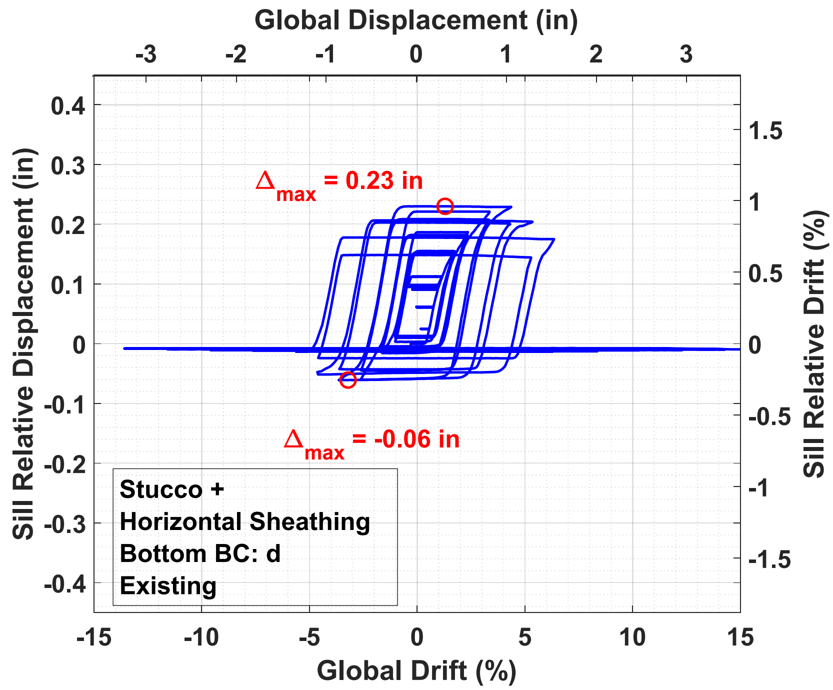


Figure 3.50 Specimen A-20 sill plate to foundation relative displacement versus *global* drift.

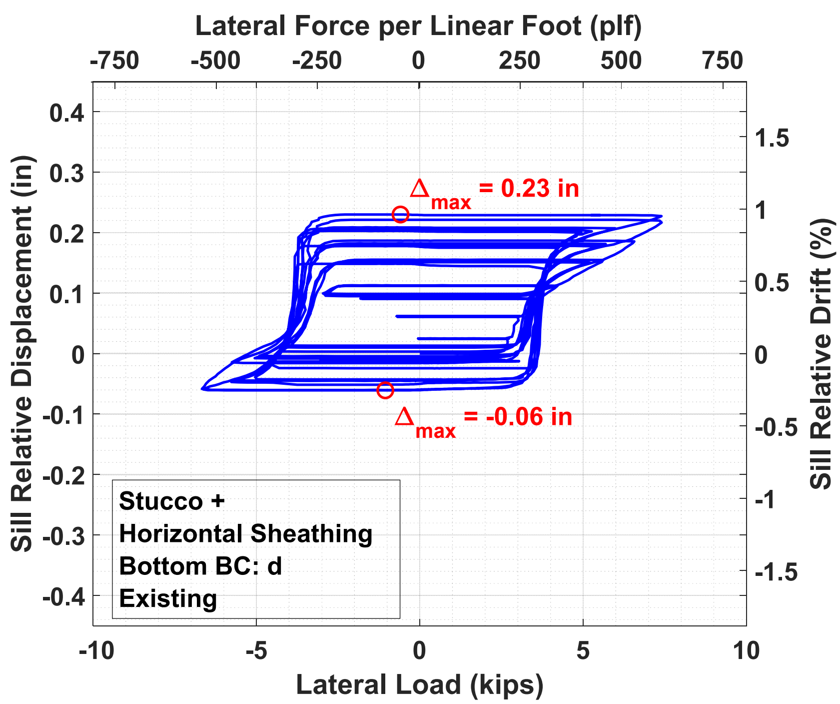


Figure 3.51 Specimen A-20 sill plate to foundation relative displacement versus lateral strength.

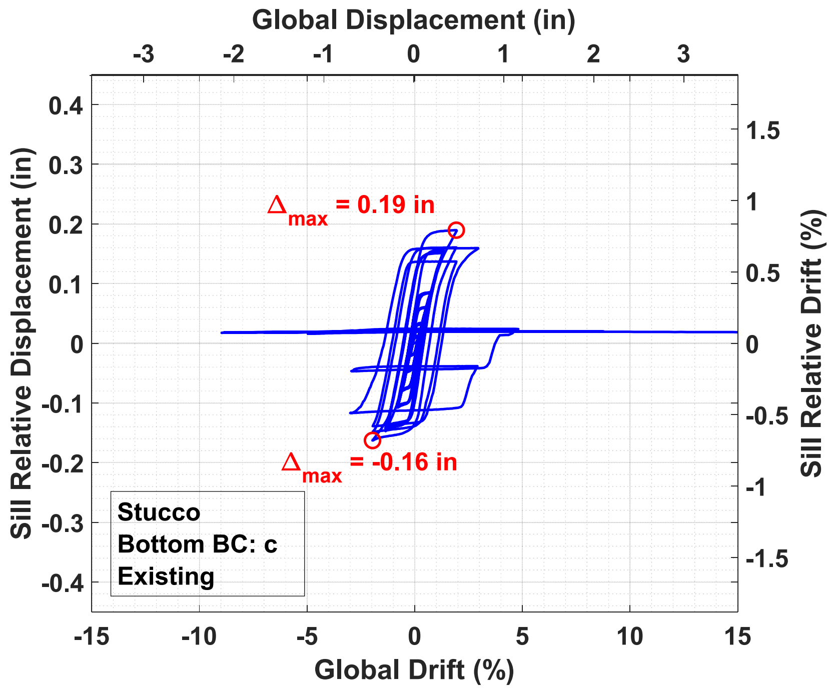


Figure 3.52 **Specimen A-22 sill plate to foundation relative displacement versus *global* drift.**

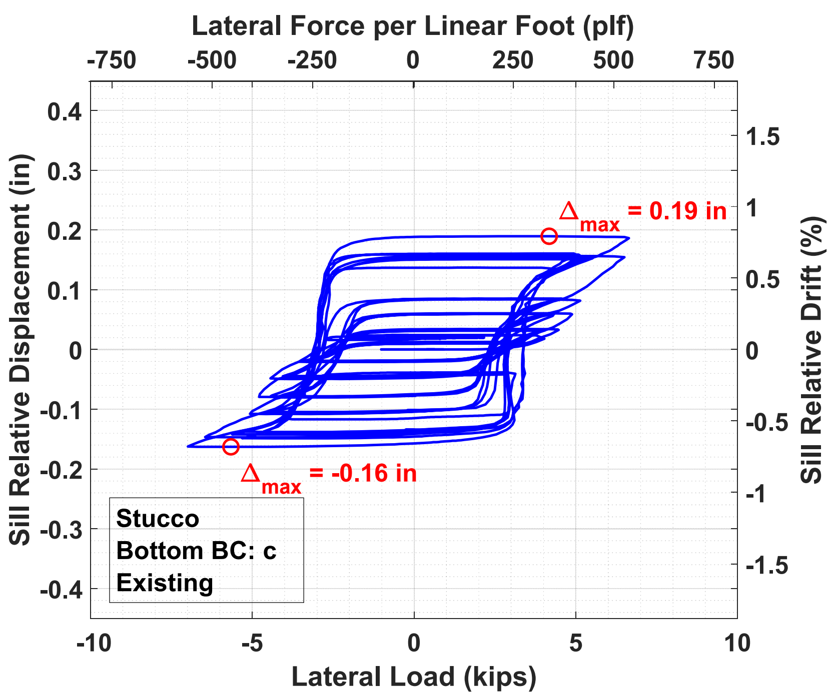


Figure 3.53 **Specimen A-22 sill plate to foundation relative displacement versus lateral strength.**

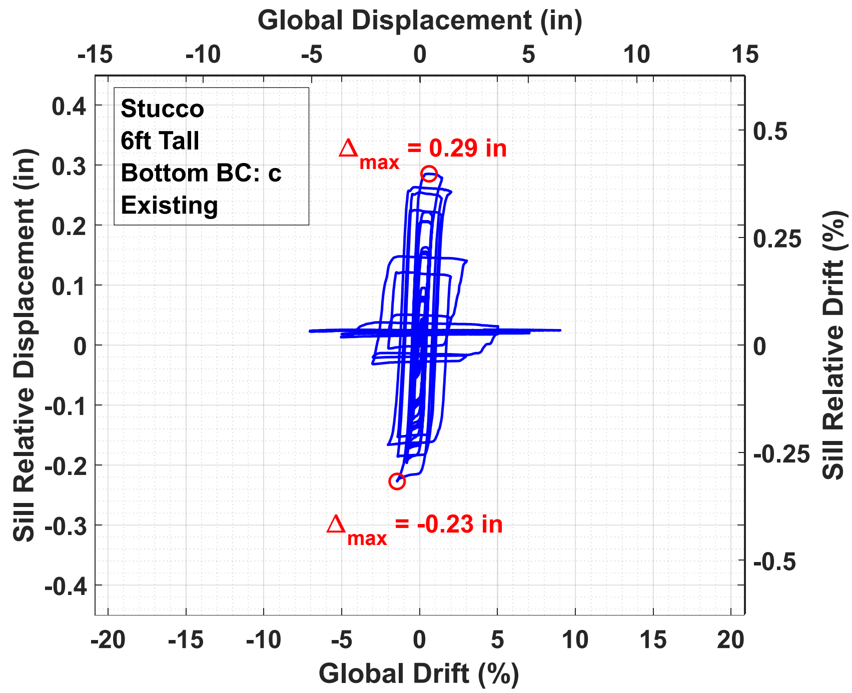


Figure 3.54 Specimen A-25 sill plate to foundation relative displacement versus *global* drift.

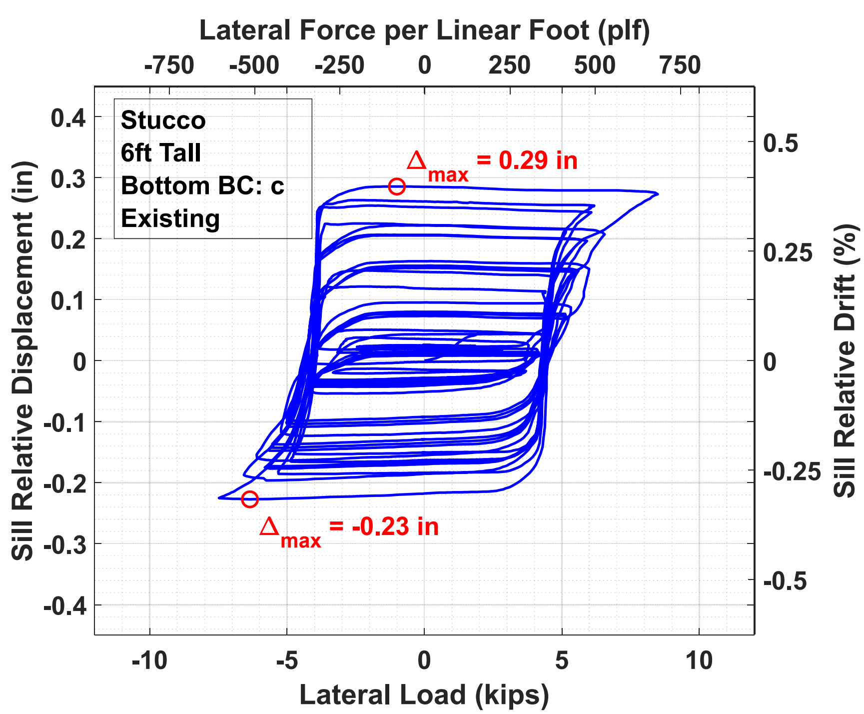


Figure 3.55 Specimen A-25 sill plate to foundation relative displacement versus lateral strength.

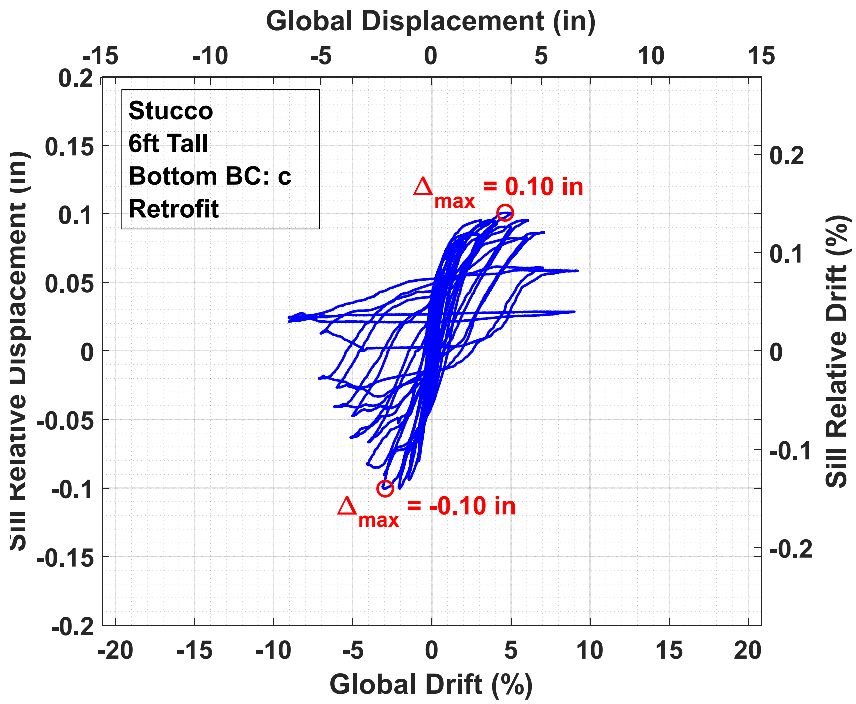


Figure 3.56 Specimen A-26 sill plate to foundation relative displacement versus ***global*** drift.

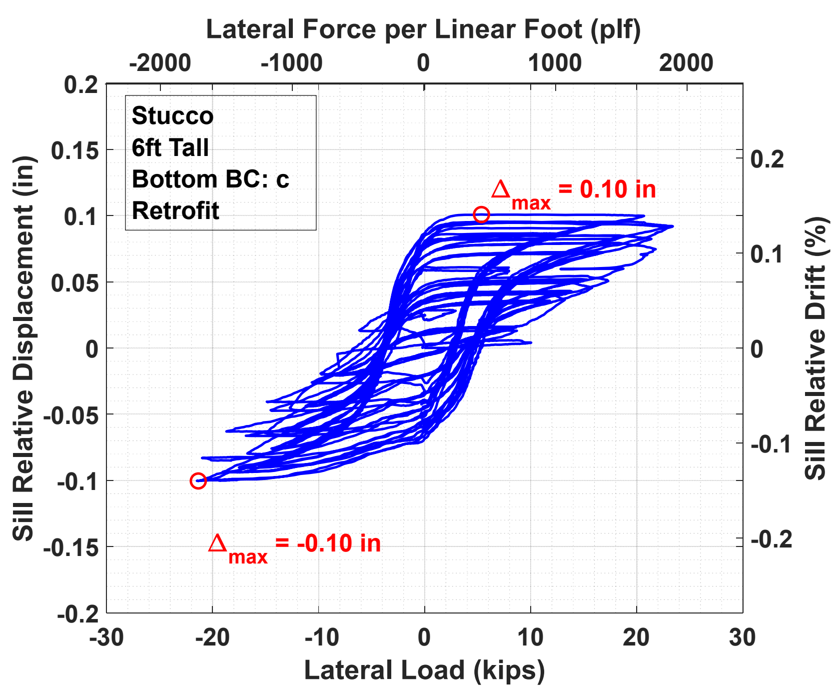


Figure 3.57 Specimen A-26 sill plate to foundation relative displacement versus lateral strength.

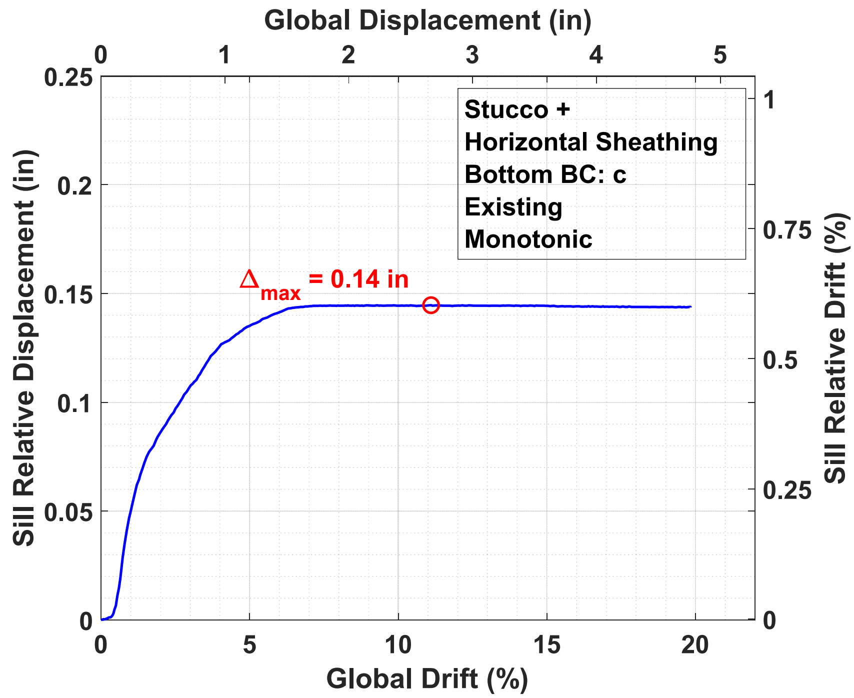


Figure 3.58 Specimen A-27 sill plate to foundation relative displacement versus ***global*** drift.

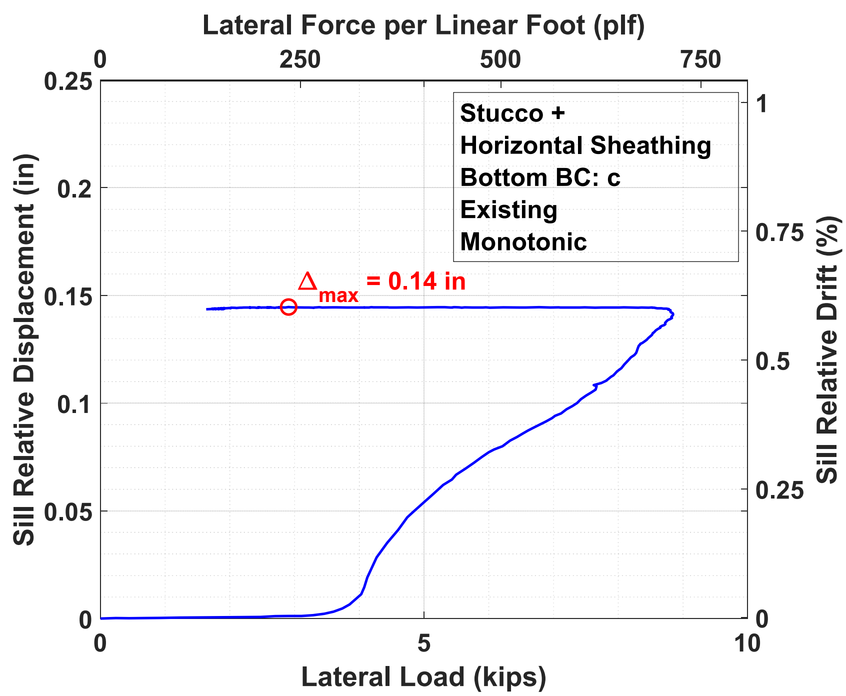


Figure 3.59 Specimen A-27 sill plate to foundation relative displacement versus lateral strength.

3.3.1 Sill Plate to Foundation Friction

In many of the tests, the global and relative response varied significantly due to the displacement of the sill plate relative to the foundation. To facilitate displacement of the sill plate along the foundation, the load imposed on the cripple wall must overcome the frictional force between the sill plate and foundation. This frictional force is dependent on the weight of the cripple wall, the vertical load on the cripple wall, and the tensile forces in the anchor bolts fastening the sill plate to the foundation.

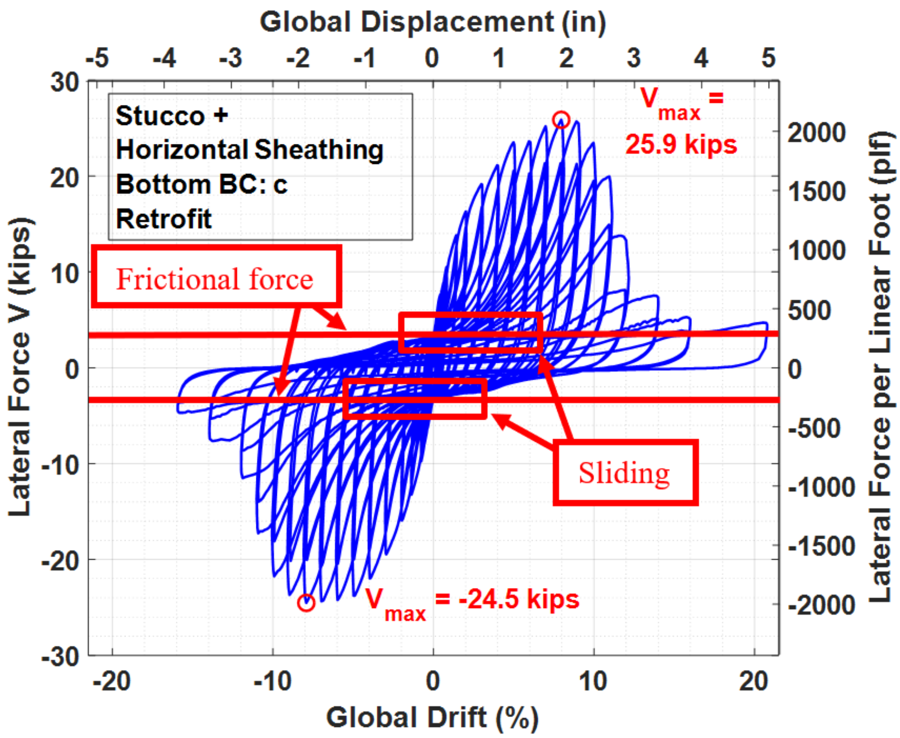
Figure 3.60 gives a visual of the difference between the global and relative response, and the associated frictional force preventing the cripple wall from displacing relative to the sill plate. Since the normal force and the lateral force are known, the coefficient of friction between the cripple wall sill plate and the foundation can be estimated by using the following equation:

$$V = \mu N$$

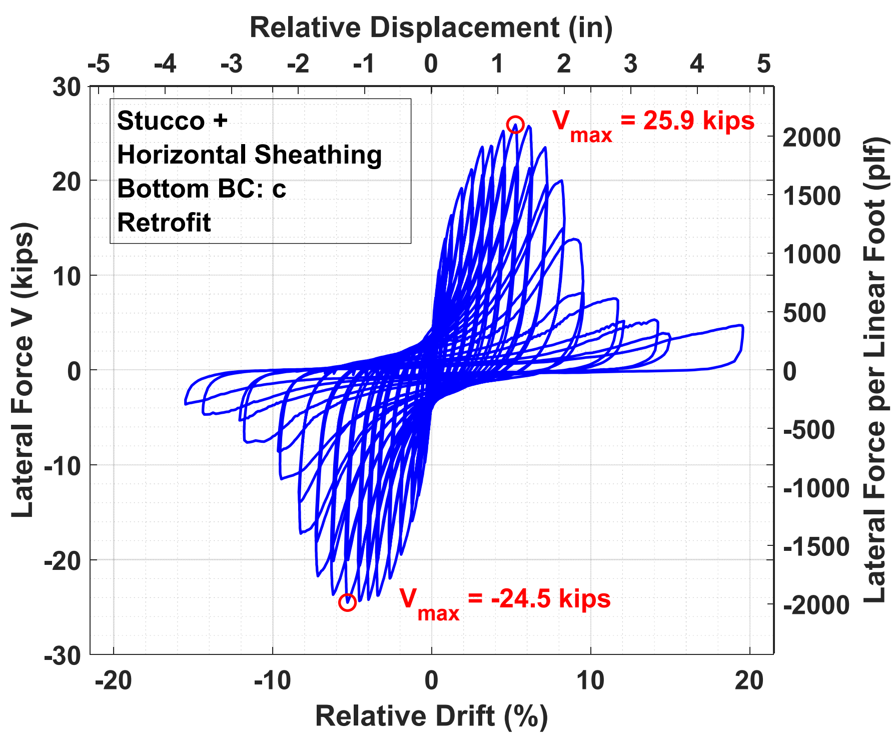
$$where, V = lateral\ load, N = normal\ force, \mu = static\ coefficient\ of\ friction$$

$$\therefore \mu = {}^{V}\!/_{N}$$

The vertical load for all specimens is 450 plf or 5.5 kips, although during testing the applied vertical load fluctuated. The weight of the cripple walls varied depending on the construction details and density of the lumber. Higher moisture contents in the lumber equates to a slightly heavier specimen. The amount of material used for all cripple walls—which had displacements of the sill plate relative to the foundation—was equal with the exception of the cripple wall with the return walls. The weight was 0.38–0.49 kips for the 2-ft-tall cripple walls and 1.02–1.17 kips for the 6-ft-tall cripple walls. The anchor bolts were tensioned to around 0.2 kips. The amount of lateral load imposed to initiate sliding also varied. These variations can be attributed to the different tension in anchor bolts from test to test and the anticipated range in static coefficient due to nominal material interface variability. Accounting for the variations in anchor bolt tensions, the static coefficient of frictions between the sill plate and the foundation for all specimens that had displacements between the sill plate and foundation can be found in Table 3.2. The average static coefficient of friction for all specimens that had displacement of the sill plate relative to the foundation is approximated to be 0.62, with a range of values from 0.52–0.73. The static coefficient of friction between dry wood and concrete has been measured as 0.62 [Aira et al. 2014].



(a)



(b)

Figure 3.60 **Global and relative responses showing the frictional force between the sill plate and foundation: (a) *global* response; and (b) *relative* response.**

Table 3.2 Static coefficient of friction calculation.

Specimen	Total vertical load (kips)	Total anchor bolt loads (kips)	Frictional force (kips)	μ_{static}
A-15	5.25	0.6	3.5	0.60
A-16	5.60	1.3	4.1	0.60
A-17	4.40	0.6	3.5	0.70
A-18	6.14	1.4	4.2	0.56
A-19	6.20	1.3	3.9	0.52
A-20	5.46	0.6	3.8	0.63
A-22	4.47	0.6	3.1	0.61
A-25	5.18	0.6	4.2	0.73
A-26	5.85	1.3	4.3	0.61
Average static coefficient of friction = 0.62				

3.4 ANCHOR BOLT LOADS AND FAILURES

To measure the tension developed in each anchor bolt, 10-kip donut load cells were placed on top of the square plate washers, as shown in Figure 3.4. For existing cripple walls, three anchor bolts were used, spaced at 64 in. on center. The anchor bolt layout for these cripple walls can be seen in Figure 3.61. For retrofitted cripple walls, additional anchor bolts were added as per the *FEMA P-1100* retrofit guidelines. For all retrofitted 2-ft-tall cripple walls, four additional anchor bolts were added. The typical spacing for anchor bolts in the retrofitted cripple walls was 32 in. on center. Two additional anchor bolts were epoxied into place 12-in. inward of the outermost anchor bolts, with an embedment depth of 10-in. into the foundation. Figure 3.62 shows the anchor bolt layout for retrofitted 2-ft-tall cripple walls. For the retrofitted 6-ft-tall specimen, four additional anchor bolts were also added. Two of these anchor bolts were attached to tie-downs on both ends of the specimen. Due to the position of the cripple wall on the foundation, the anchor bolt slots could not accommodate the anchor bolts fastened to the tie-downs. Because of this, the anchor bolts were embedded 10-in. into the foundation and epoxied into place. Therefore, a total of four anchor bolts were epoxied and three anchor bolts were slotted, as shown in Figure 3.63. All anchor bolts were tensioned to around 200 lbf prior to testing, which is what has been observed in the field. Initial anchor bolt loads are provided in Table 3.4.

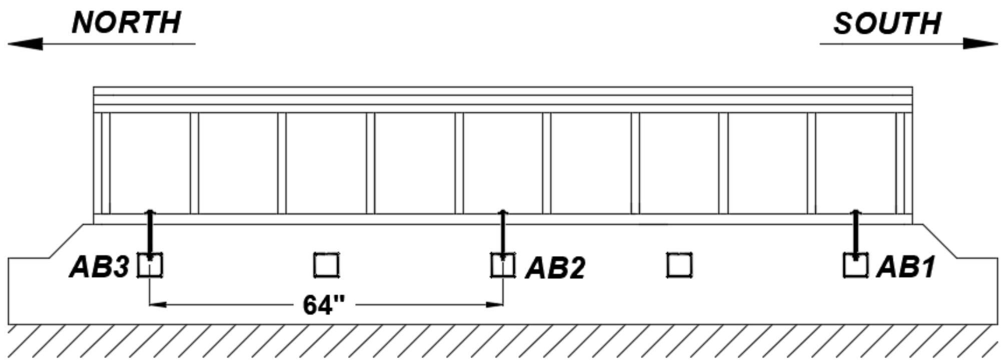


Figure 3.61 Three anchor bolt layout for existing cripple walls.

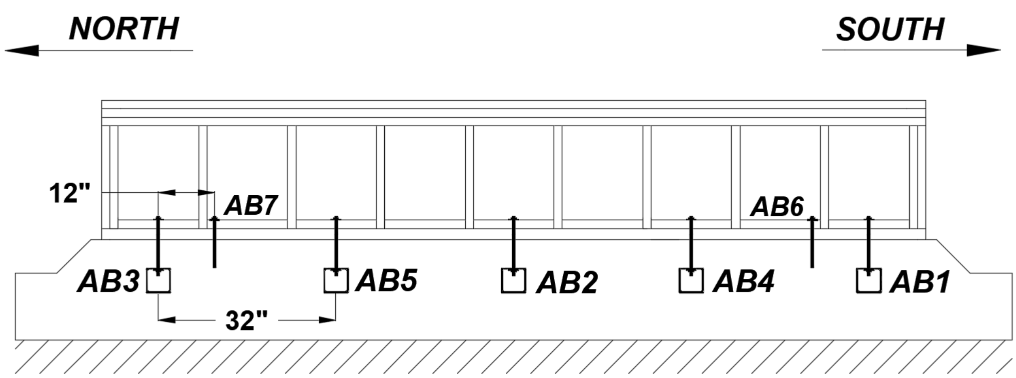


Figure 3.62 Seven anchor bolt layout for retrofitted cripple walls.

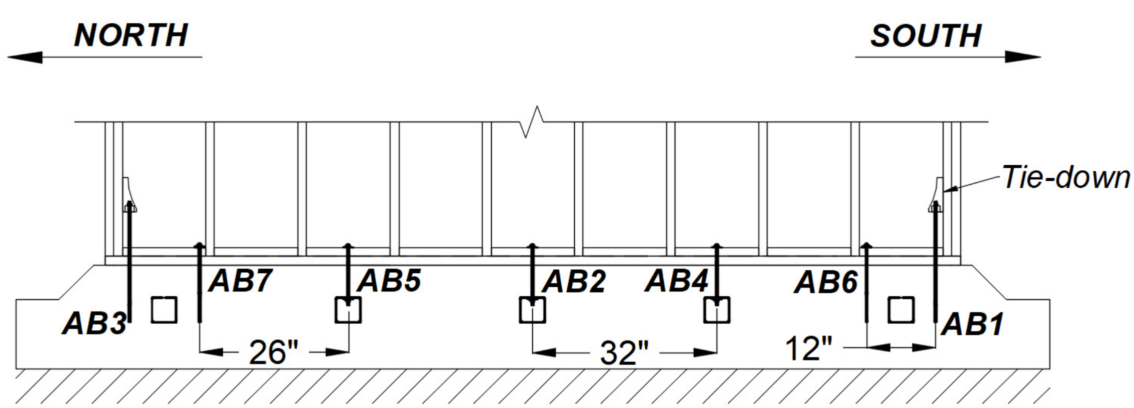


Figure 3.63 Seven anchor bolt layout with tie-downs for retrofitted 6-ft-tall cripple walls.

The maximum loads experienced by each anchor bolt during testing is shown in Table 3.3. In general, the retrofitted cripple walls experienced the highest anchor bolt. The increased anchor bolt loads were due to the large lateral loads experienced by these cripple walls during testing. Specimen A-15, an existing cripple wall with stucco over horizontal sheathing, had the largest anchor bolt loads of any of the existing specimens, which was a result of this specimen having the highest strength of any of the existing specimens. The lowest anchor bolt loads were experienced by Specimen A-25, which was an existing 6-ft-tall cripple wall with a stucco exterior finish. The anchor bolt loads rarely exceeded their initial loads throughout the entire test. The highest anchor bolt loads were experienced by the retrofit counterpart of Specimen A-25 at the locations of the tie-downs. The tie-downs resisted the uplifting force of not only the sill plate, as is with typical anchor bolts, but also the end framing, which caused a large increase in the anchor bolts loads compared with specimens without tie-downs. The maximum loads that the anchor bolts at the tie-down locations experienced was 7.64 kips for AB3 and 7.38 kips for AB1. No other anchor bolt for any specimen exceeded 5 kips. Typical values for existing 2-ft-tall specimens were in the range of 0.70–2.85 kips; if the cripple wall finished with stucco over diagonal sheathing were ignored, the range would narrow to 0.70–1.73 kips.

Tables 3.5 and 3.6 provide the anchor bolt loads experienced at peak loading in the push and pull directions, respectively. Note that the cripple walls were pushed in south direction and pulled north direction. When loaded in the push direction, the anchor bolts on the north end of the walls saw increases in load as they resisted the uplift and sliding of the cripple wall, and vice versa when loaded in the pull direction. All cripple walls exhibited this trend. Tables 3.7 and 3.8 show differences in anchor bolt loads in the push and pull directions from their initial loads, respectively. All horizonal siding over diagonal sheathing finished cripple wall anchor bolts exhibited large increases in loads as the test progressed, regardless of the direction of loading.

Table 3.3 Anchor bolt maximum loads (in kips) for all cripple walls.

Specimen	South			Center	North		
	AB3	AB7	AB5	AB2	AB4	AB6	AB1
A-15	2.85			2.10			1.94
A-16	4.86	0.94	2.35	3.72	3.89	3.61	4.14
A-17	1.00			0.87			1.30
A-18	2.99	2.53	1.99	2.68	1.99	2.52	3.04
A-19	2.93	3.69	3.47	1.12	4.60	1.88	3.86
A-20	0.70			1.02			1.30
A-22	1.27			0.57			1.37
A-25	1.66			0.81			1.73
A-26	7.64	2.77	2.20	2.27	1.28	0.94	7.38
A-27	0.25			0.29			0.16

Table 3.4 Initial anchor bolt tension (in kips) at start of test.

Specimen	South			Center	North		
	AB3	AB7	AB5	AB2	AB4	AB6	AB1
A-15	0.20			0.19			0.18
A-16	0.16	0.18	0.18	0.18	0.18	0.19	0.19
A-17	0.18			0.20			0.19
A-18	0.20	0.21	0.25	0.19	0.19	0.18	0.18
A-19	0.15	0.17	0.19	0.20	0.18	0.19	0.15
A-20	0.19			0.23			0.16
A-22	0.18			0.21			0.21
A-25	0.18			0.21			0.20
A-26	0.18	0.18	0.15	0.19	0.21	0.16	0.19
0.18	0.25			0.18			0.16

Table 3.5 Anchor bolt load (in kips) at peak load in the *push* loading direction.

Specimen	South			Center	North		
	AB3	AB7	AB5	AB2	AB4	AB6	AB1
A-15	2.42			1.05			0.98
A-16	4.02	0.94	0.88	0.00	0.99	0.12	0.08
A-17	1.29			0.87			0.05
A-18	2.63	2.43	0.93	0.71	1.16	0.02	0.01
A-19	2.56	0.02	2.67	0.55	2.65	0.01	0.54
A-20	1.27			0.06			0.65
A-22	1.33			0.13			0.27
A-25	1.66			0.79			0.49
A-26	7.39	2.76	0.36	0.87	0.93	0.35	0.00
A-27	0.25			0.28			0.09

Table 3.6 Anchor bolt load (in kips) at peak load in the *pull* loading direction.

Specimen	South			Center	North		
	AB3	AB7	AB5	AB2	AB4	AB6	AB1
A-15	1.71			1.27			1.78
A-16	0.42	0.09	2.20	2.40	3.89	0.00	4.14
A-17	0.81			0.58			0.80
A-18	0.37	1.02	1.67	1.82	1.47	2.49	2.67
A-19	2.18	0.00	2.35	0.01	4.60	0.16	3.61
A-20	0.45			1.02			0.35
A-22	0.36			0.57			1.27
A-25	0.74			0.47			1.73
A-26	0.00	0.37	2.20	1.28	0.63	0.94	6.87

Table 3.7 **Difference in anchor bolt loads (in kips) at peak *push* load to initial anchor bolt loads.**

Specimen	South			Center	North		
	AB3	AB7	AB5	AB2	AB4	AB6	AB1
A-15	2.22			0.86			0.79
A-16	3.86	0.76	0.70	-0.17	0.82	-0.06	-0.11
A-17	1.11			0.66			-0.14
A-18	2.43	2.21	0.68	0.52	0.97	-0.15	-0.18
A-19	2.41	-0.15	2.47	0.35	2.46	-0.18	0.39
A-20	1.08			-0.17			0.49
A-22	1.15			-0.08			0.06
A-25	1.48			0.58			0.29
A-26	7.21	2.58	0.22	0.68	0.72	0.18	-0.18
A-27	0.07			0.10			-0.07

Table 3.8 **Difference in anchor bolt loads (in kips) at peak *pull* load to initial anchor bolt loads.**

Specimen	South			Center	North		
	AB3	AB7	AB5	AB2	AB4	AB6	AB1
A-15	1.51			1.08			1.59
A-16	0.26	-0.09	2.02	2.23	3.71	-0.18	3.95
0.63	0.81			0.37			0.61
A-18	0.17	0.81	1.43	1.62	1.28	2.31	2.49
A-19	2.03	-0.19	2.15	-0.19	4.41	-0.03	3.46
A-20	0.26			0.79			0.19
A-22	0.18			0.36			1.06
A-25	0.57			0.26			1.53
A-26	-0.18	0.18	2.05	1.09	0.43	0.77	6.68

Both specimens finished with stucco over diagonal sheathing experienced anchor bolt fracture during testing. The existing specimen suffered one anchor bolt fracture, while all seven anchor bolts in the retrofitted specimen fractured. Figure 3.64 provides the anchor bolt versus global drift response of Specimen A-15, the existing cripple wall. Figure 3.65 provides the lateral force–global displacement hysteresis for the specimen with an indication of where in the response the anchor bolt fracture occurred; this figure is accompanied by a schematic of the anchor bolt layout for the specimen; see Figure 3.66. While only one anchor bolt fractured during testing, a cross-grain crack formed along the entire sill plate, propagating through all anchor bolt holes. Figure 3.70 shows a photograph of the fractured anchor bolt as well as damage to the sill plate at the location of the fractured anchor bolt.

For the retrofitted specimen, all seven anchor bolts fractured at various points during testing. Figures 3.67 through 3.69 provide the anchor bolt loads versus global drift, hysteretic response with locations of anchor bolt fractures, and a schematic of the anchor bolt locations. In Figure 3.71, a photograph of one of the fractured anchor bolts is shown along with the damage to the sill plate. As with Specimen A-16, Specimen A-15 experienced cross-grain splitting of the sill plate. The fractures were a result of both shear and flexural forces on the anchor bolts. Once one anchor bolt fracture occurred, the shear and flexural forces increased on the other anchor bolts. As the cripple walls continued to gain strength, the anchor bolts could not resist these forces, eventually causing all anchor bolts to fracture. Although Specimen A-26 had the highest anchor bolt loads experience, there were no fractures. These anchor bolts were connected to the tie-downs; therefore, they were more in tension from the cripple wall uplifting than flexure and shear from the wall displacing. Figures 3.69 and 3.70 show images of the anchor bolt failures for both specimens.

Many of the cripple walls tested developed cross-grain cracks in the sill plates, but they were most severe in the specimens with diagonal sheathing. As the cripple walls displaced the diagonal sheathing and uplifted, large stresses developed in the sill plate. Since the sheathing material was only nailed to the exterior of the cripple wall, the sill was subjected to cross-grain bending, which resulted in a full span crack of the sill through all anchor bolt slots. In the case of Specimen A-15, the sill plate couldn't provide any resistance, with the result that the cripple wall strength dramatically decreased even through there was not any significant damage to the finish materials or framing besides the sill plate. Photographs of the damage to the sill plate are provided in Figure 3.71. All anchor bolt loads versus global drift hysteresis are shown in Appendix C.1.

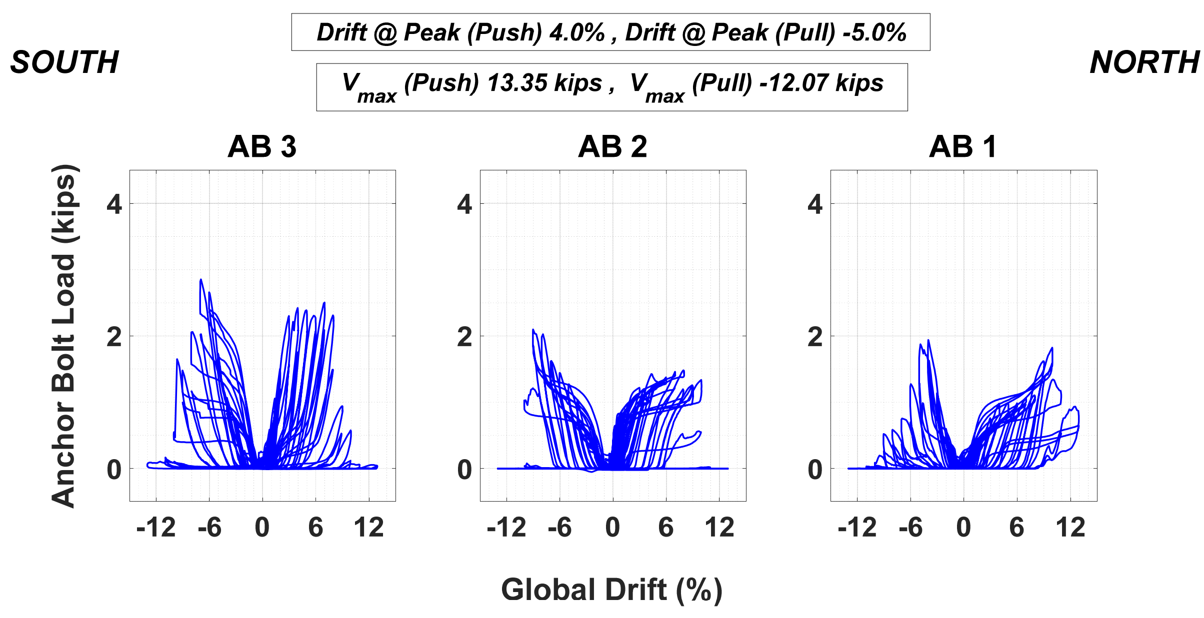


Figure 3.64 **Specimen A-15 anchor bolt load versus *global* drift of the existing 2-ft-tall cripple wall with stucco over diagonal sheathing.**

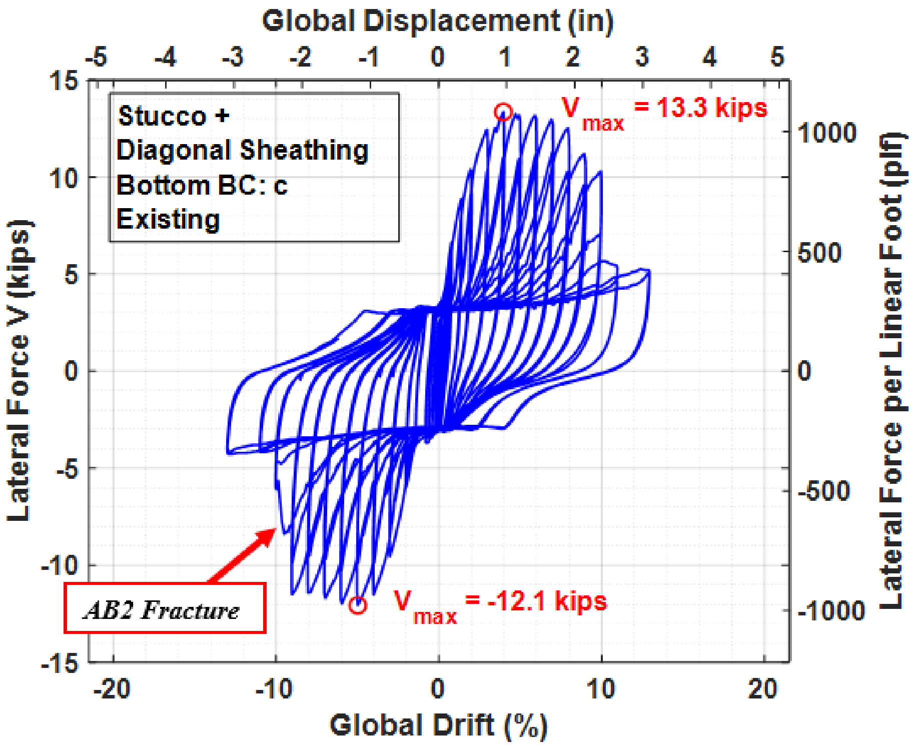


Figure 3.65 Specimen A-15 location of anchor bolt fractures on lateral force versus *global* lateral drift and displacement hysteresis.

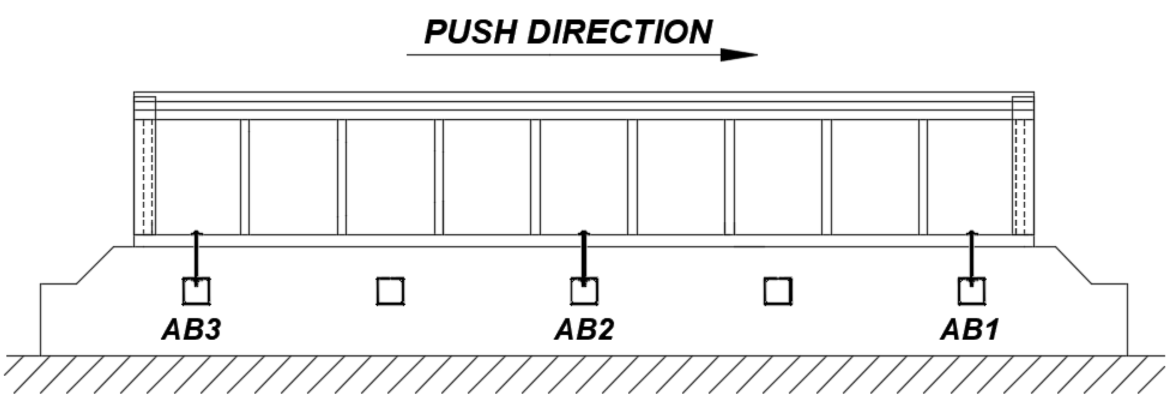


Figure 3.66 Specimen A-15 anchor bolt locations.

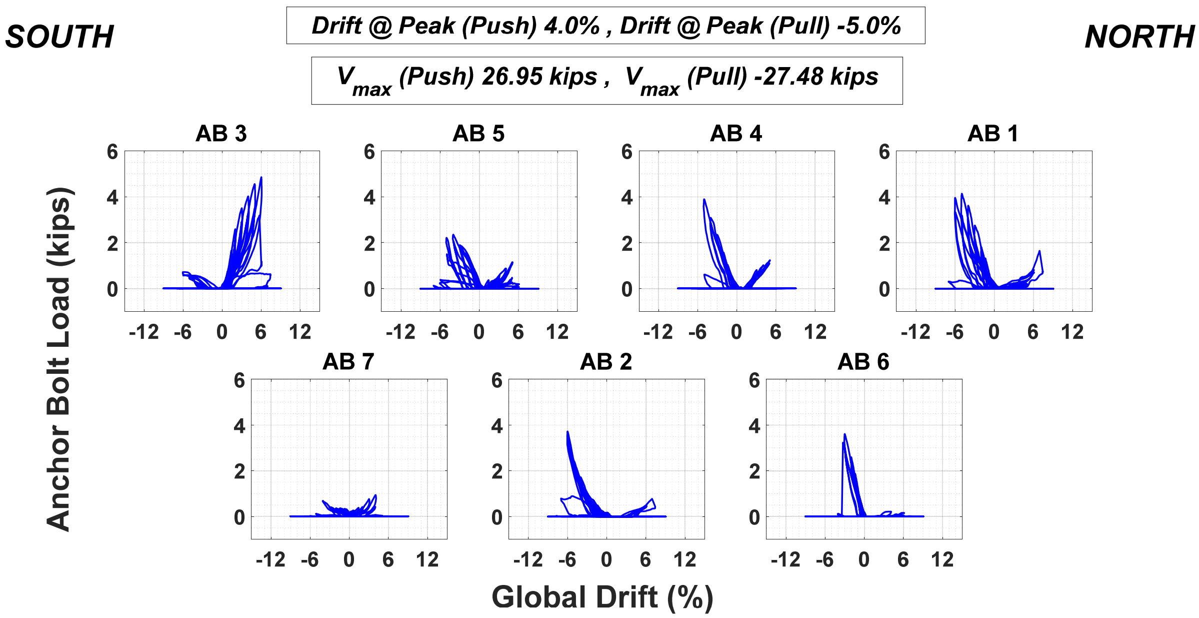


Figure 3.67 Specimen A-16 anchor bolt load versus *global* drift for the retrofitted 2-ft-tall cripple wall with stucco over diagonal sheathing.

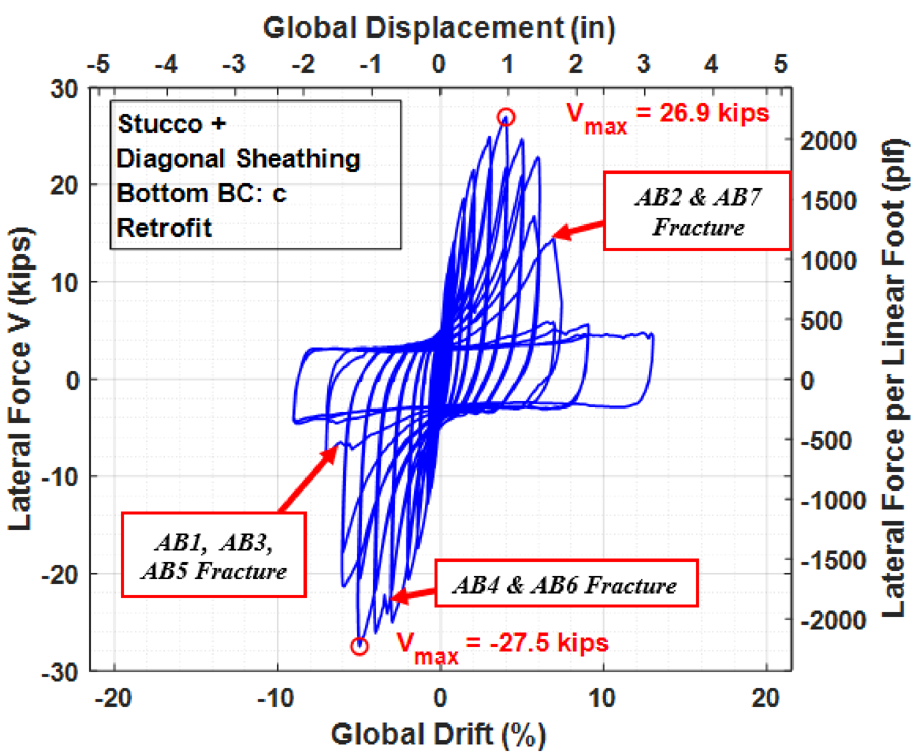


Figure 3.68 Specimen A-1 location of anchor bolt fractures on lateral force versus *global* lateral drift and displacement hysteresis.

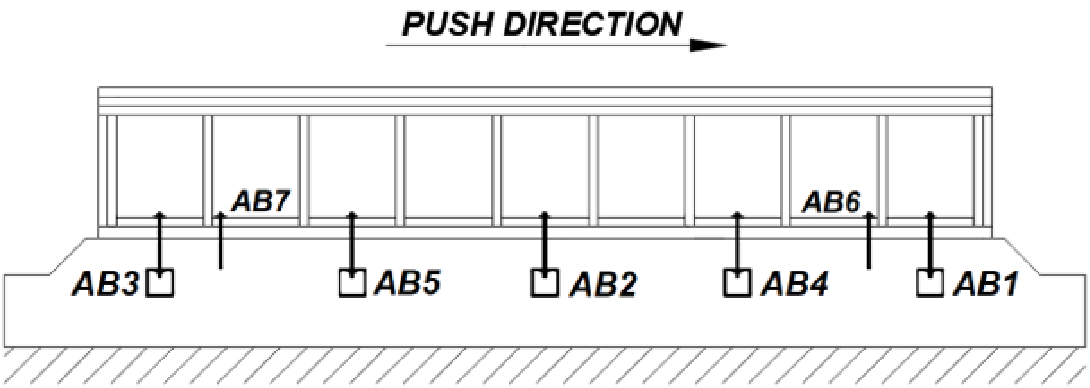


Figure 3.69 Specimen A-15 anchor bolt locations.

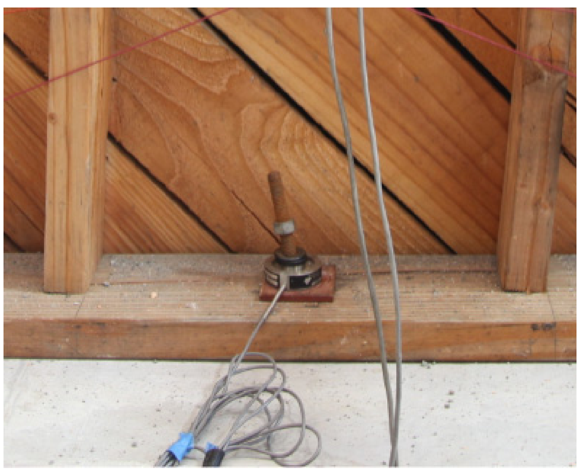


Figure 3.70 Specimen A-15 fractured anchor bolt (left) and damage to the sill plate (right).

Figure 3.71 Specimen A-15 fractured anchor bolt (left) and damage to the sill plate (right).

3.5 DIAGONAL MEASUREMENTS

Measurements were taken of the displacement across the diagonal of the cripple wall. Two sets of potentiometers were used. One pair of potentiometers measured the distortion across the entire cripple wall, while the other pair measured the distortion of the middle third of the cripple wall. The purpose of these measurements was twofold: to determine the amount of shear distortion within the cripple wall; and to determine the if the applied lateral displacement could be resolved using the diagonal and end uplift measurements. Figure 3.72 shows the linear potentiometers used to calculate the resolved lateral displacement of the cripple wall. Figure 3.73 shows the how the resolved lateral displacements from diagonal and uplift measurements were derived.

Figures 3.74 through 3.77 show the relative drift versus the relative drift resolved from the diagonal and uplift measurements for Specimen A-25 and A-26 (the existing and retrofitted 6-ft-tall cripple walls with stucco finishes). Figures 3.74 and 3.76 overlay the resolved lateral drifts from the inside diagonals on the left and the resolved lateral drifts from the outside diagonals on the right for Specimens A-25 and A-26, respectively. Figures 3.75 and 3.77 overlay the resolved lateral drifts from the diagonals running from the bottom north end of the wall to the top south end of the wall on the left, and the resolved lateral drifts running from the top north end of the wall to the bottom south end of the wall on the left for Specimen A-25 and A-26, respectively.

As a reference, all these figures include a green line indicating the measured relative drift plotted against itself. These cripple walls were chosen because they differed only in their retrofit condition. Specimen A-25, the unretrofitted cripple wall, had resolved relative drift values within 0.6% drift of the measured relative drift, a difference that tended to be less than that for most of the test and only diverging at later drift amplitudes. On average between push and pull loading, the relative drift resolved from the inside diagonals differed by 0.3% relative drift and the relative drift resolved from the outside diagonals differed by 0.6% relative drift. These values increased for the differences between the measured relative drift and resolved relative measurements from the inside diagonals for the retrofitted cripple wall, with an average difference of 4.2%, while the difference for the measured relative drift and resolved relative drift of the outside diagonals was 0.9% relative drift. This shows that the addition of the plywood panels for the retrofit reduced the shear distortion through the interior of the cripple wall where the panels were attached. Overall, the pattern was the same for all existing and retrofitted cripple walls. All resolved relative drift figures are shown in Appendix C.2.

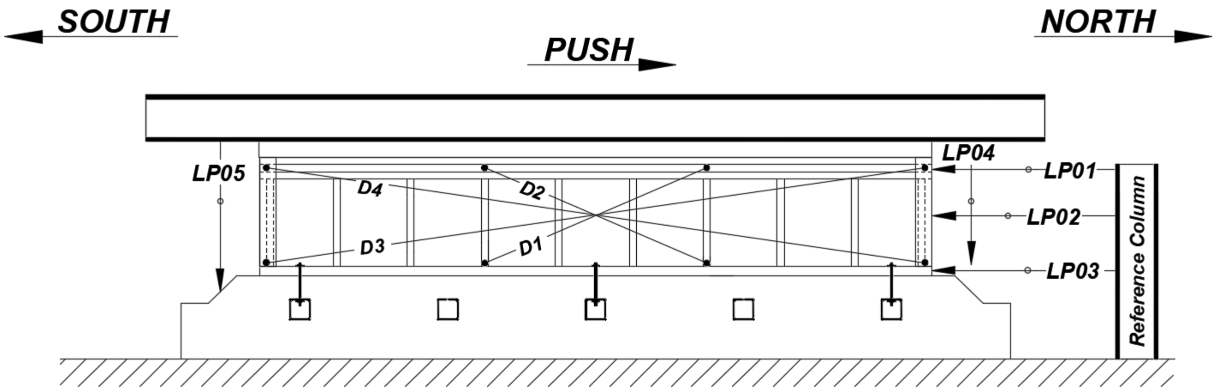


Figure 3.72 Diagonal, end uplift, and lateral displacement potentiometer schematic.

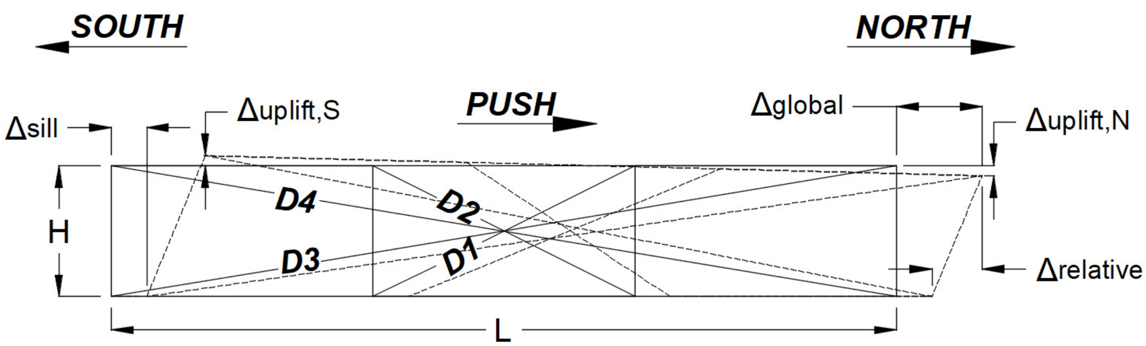


Figure 3.73 Deformed cripple wall with measurements used for resolving lateral displacement from diagonal and uplift measurements.

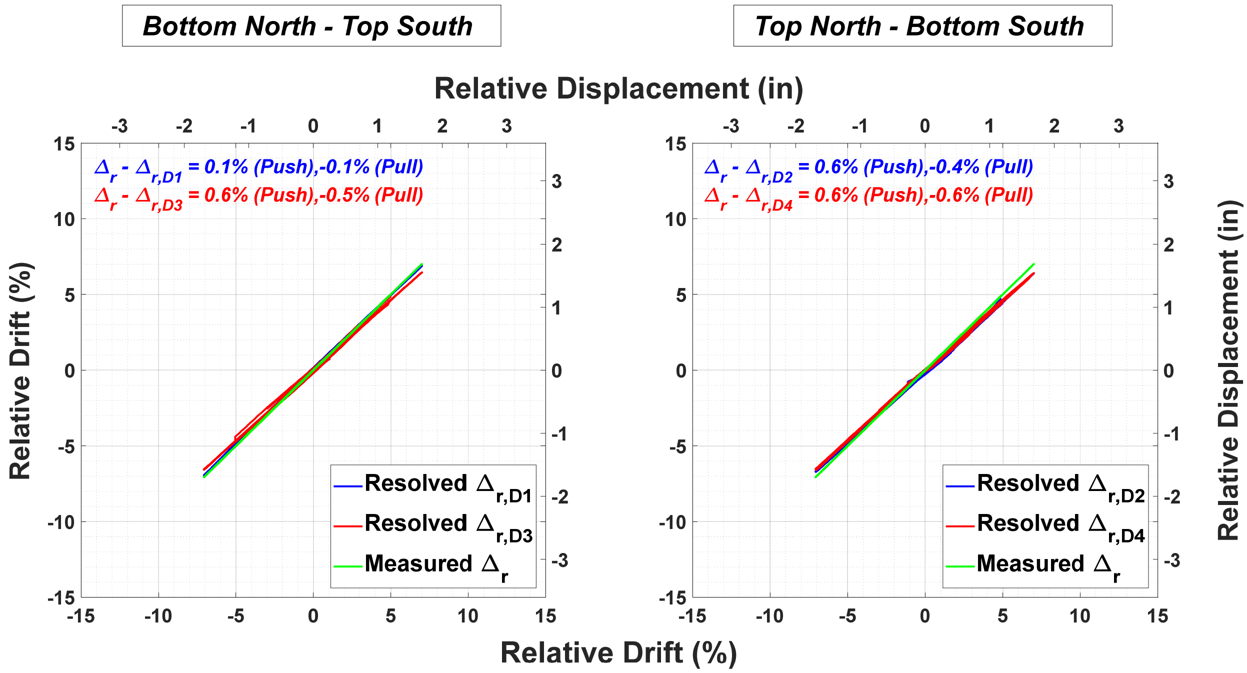


Figure 3.74 Specimen A-25 resolved relative drift from diagonal measurements in one direction versus measured relative drift for the existing 6-ft-tall cripple wall with stucco exterior finish and bottom boundary condition "c".

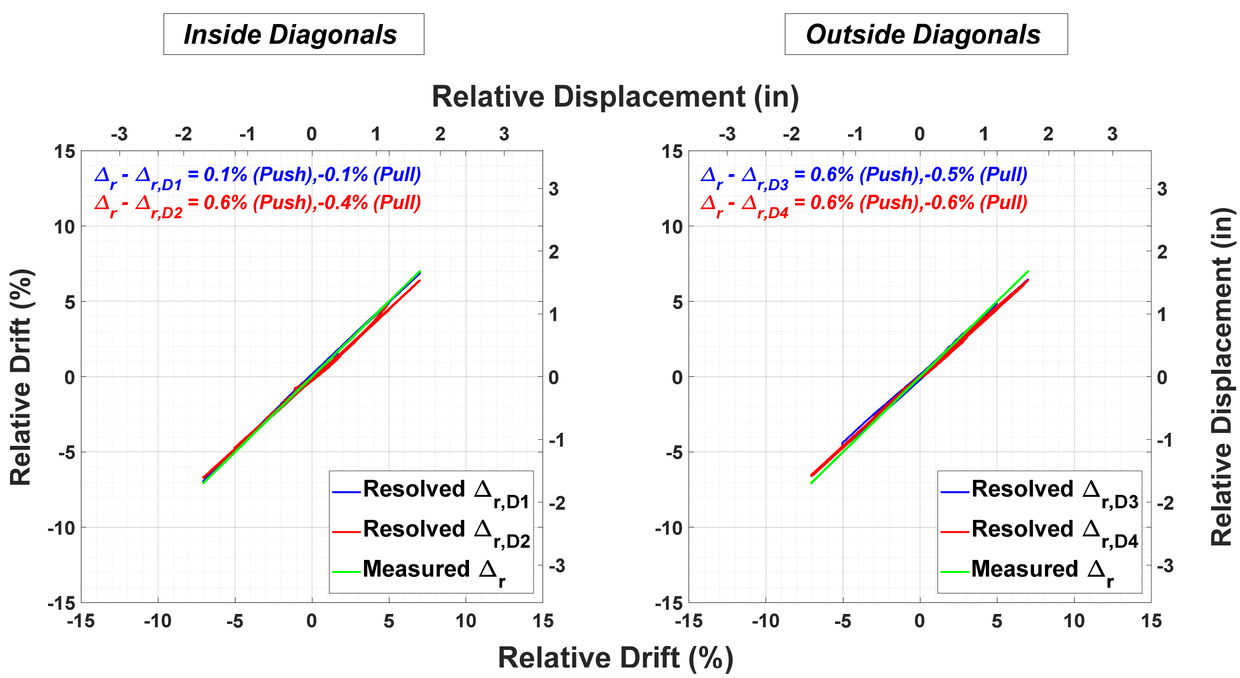


Figure 3.75 Specimen A-25 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift for the existing 6-ft-tall cripple wall with stucco exterior finish and bottom boundary condition "c".

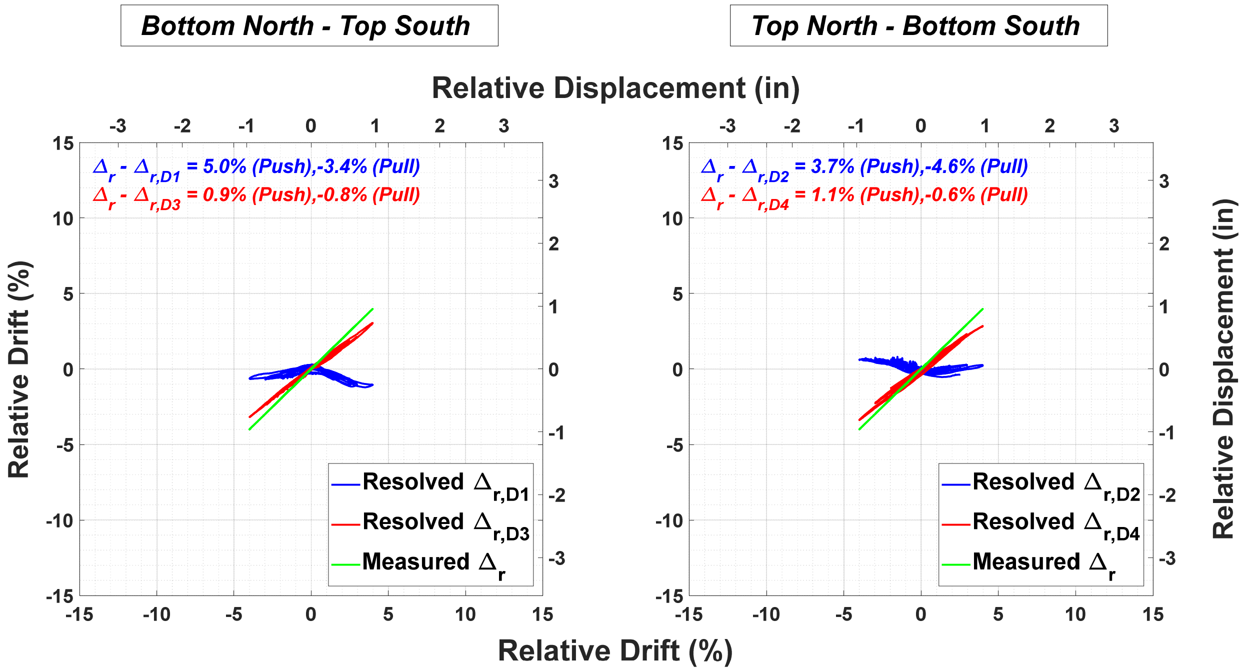


Figure 3.76 Specimen A-26 resolved relative drift from diagonal measurements in one direction versus measured relative drift for the retrofitted 6-ft-tall cripple wall with stucco exterior finish and bottom boundary condition “c”.

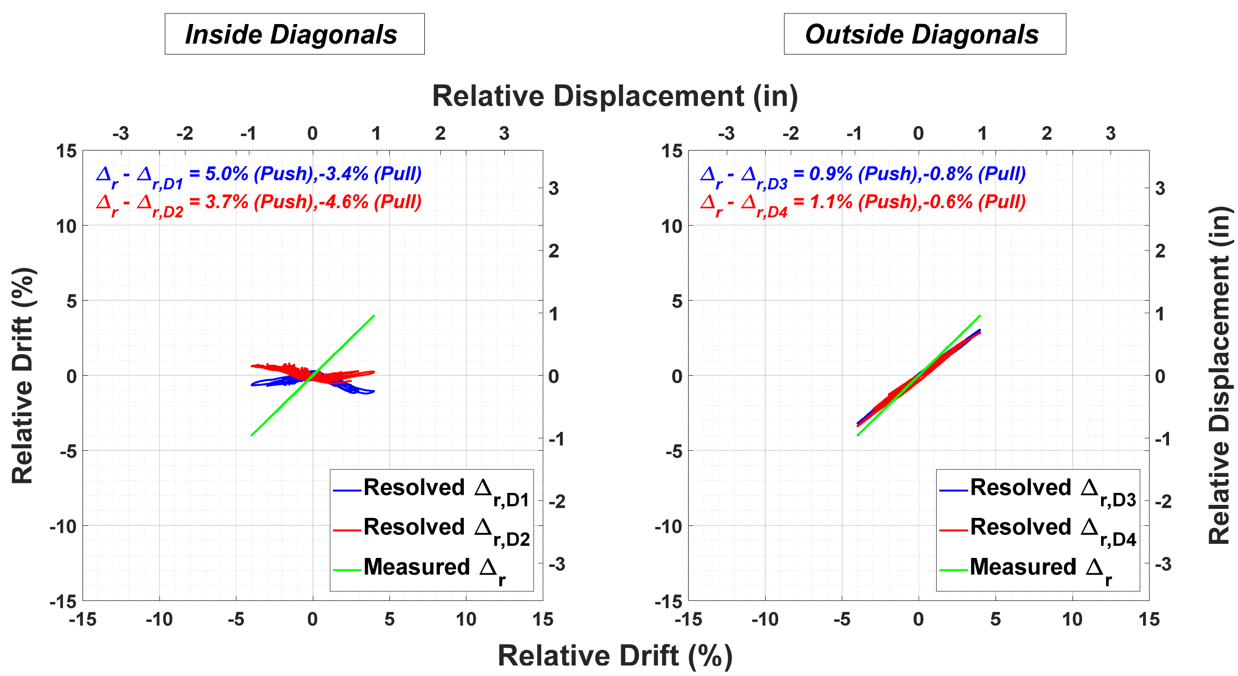


Figure 3.77 Specimen A-26 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift for the retrofitted 6-ft-tall cripple wall with stucco exterior finish and bottom boundary condition “c”.

3.6 UPLIFT MEASUREMENTS

Two linear potentiometers were used to measure the uplift at both ends of the cripple wall. These potentiometers were attached to the foundation and the steel load transfer beam. The calculations for determining the uplift of the cripple walls is shown in the previous section as the uplift measurements were factored into calculating the resolved relative displacement from the diagonal measurements. Table 3.9 summarizes of the maximum uplift measurement at each end of the wall for all specimens. All cripple walls experienced uplift at the ends when being displaced, with the exception of the existing cripple walls finished with horizontal sheathing. Figures 3.78 and 3.79 show the end uplift versus relative drift response for Specimens A-17 and A-18, the existing and retrofitted 2-ft-tall specimens with stucco finishes and bottom boundary condition “d”.

At each drift ratio level, the existing specimen’s height was reduced due to the deformation of the wall and insufficient forces to overcome the uplift resistance. With the added retrofit, the deformation still occurred, but the increased strength of the cripple wall caused uplift to occur as it is greater than the uplift resistance provided by the vertical load on and weight of the specimen. The addition of the retrofit increased the end of wall uplift for all specimens. For the existing cripple walls with stucco over diagonal sheathing, there was a drastic difference in the uplift at the south end versus the north end of the walls, which is attributed to the orientation of the diagonal sheathing boards. When loaded in the pull direction, the sheathing board moved both laterally and vertically upward, whereas the sheathing boards moved laterally and vertically downward in the opposite direction of loading. This caused the uplift to be strongly governed by the direction of loading. The largest end uplifts were measured for the retrofitted 6-ft-tall specimen with stucco exterior finish. All end uplift versus relative drift responses is shown in Appendix C.3.

Table 3.9 End uplift measurements.

Specimen no.	South-end uplift (in.)	North-end uplift (in.)
A-15	0.12	0.56
A-16	0.31	0.40
A-17	0	0
A-18	0.23	0.14
A-19	0.64	0.92
A-20	0.02	0.03
A-21	0	0.01
A-22	0	0
A-25	0.16	0.08
A-26	0.83	1.02
A-27	0	0

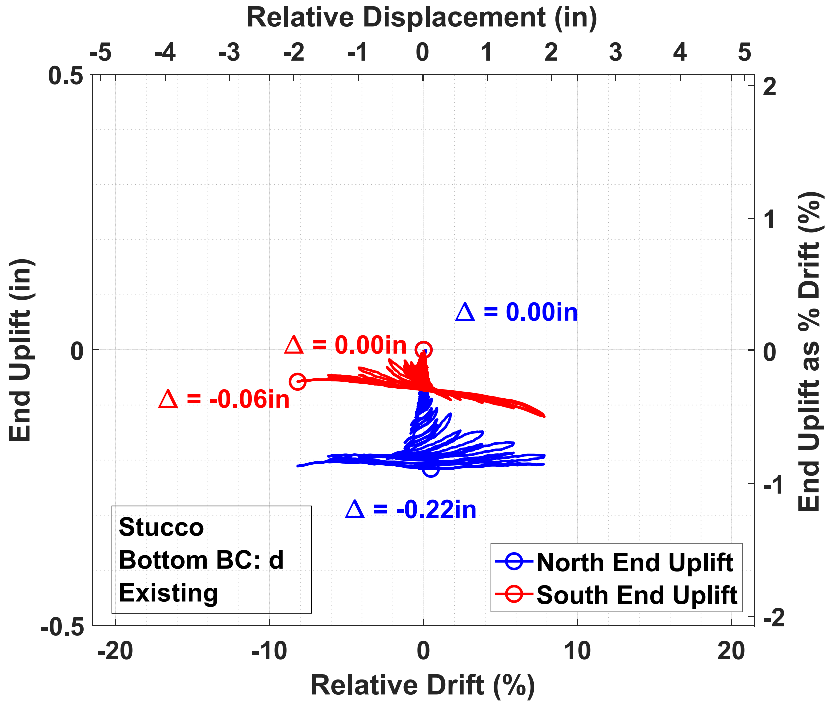


Figure 3.78 Specimen A-17 end uplift versus *relative* drift for the existing 2-ft-tall cripple wall with stucco exterior finish and bottom boundary condition "c".

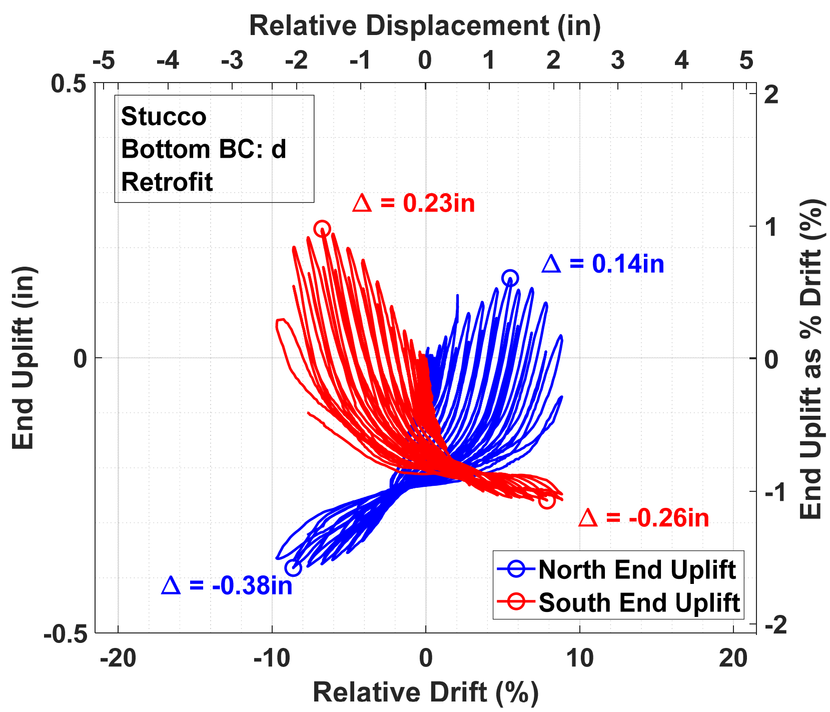


Figure 3.79 Specimen A-18 end uplift versus *relative* drift for the retrofitted 2-ft-tall cripple wall with stucco exterior finish and bottom boundary condition "d".

3.7 COMPARISON OF RETROFITTED CRIPPLE WALLS

One of the major goals of this project was to understand and quantify the effectiveness retrofitting cripple walls. Four pairs of cripple walls with retrofits and wet exterior finishes were tested in this project; three are discussed herein. Since the performance of bottom boundary condition "d" was nearly identical to that of bottom boundary condition "c", an additional retrofit pair will be incorporated in this discussion with Specimen A-20 (the existing 2-ft-tall cripple wall with stucco over horizontal sheathing and bottom boundary condition "d") and Specimen A-19 (the existing 2-ft-tall cripple wall with stucco over horizontal sheathing and bottom boundary condition "c").

Retrofitting cripple walls works to address vulnerabilities in the connection of the cripple wall to the framing above, the cripple wall sheathing, and the foundation sill plate anchorage to the foundation. This involves adding connectors to improve the connection from the cripple wall to the framing above, adding wood structural panels to the interior framing of the cripple wall to strengthen the cripple wall, and installing additional anchor bolts to increase the sliding resistance of the dwelling. In addition, for taller cripple walls (typically 4 ft tall or greater), tie-downs are installed to increase the uplift capacity of the dwelling. For purposes of this testing program, connectors used to improve connection from the cripple wall to the framing above were not implemented as only cripple wall components were tested. The retrofit design guidelines used in this project comes from the *FEMA P-1100* prescriptive design provisions published in December 2018 [FEMA 2018]. The *FEMA P-1100* prescriptive design provisions were the basis of the retrofit design used in this project. Details on the *FEMA P-1100* retrofit design can be found in Section 2.6.

Overall, the retrofit dramatically increased the lateral strength and stiffness of all cripple walls. In most cases, it also increased the drift capacity of the cripple wall. Figures 3.80 through 3.87 show overlays of the global and relative lateral displacement versus lateral load hysteretic response for specimen pairs. Figure 3.88 shows the lateral strength per linear foot of the five retrofitted cripple walls. Figure 3.89 shows the relative drift (total drift minus the displacement between the sill plate and foundation) at strength for the five retrofitted cripple walls. Lastly, Figure 3.90 shows the percent increase in strength of the retrofitted specimens compared to their existing counterpart.

The most significant improvement to performance for was for retrofitted Specimens A-20 versus the existing Specimen A-20, the 2-ft-tall with stucco over horizontal sheathing exterior finish. The average lateral strength per linear foot increased from 569 plf to 2037 plf, nearly a 260% increase in strength. The initial secant stiffness, defined as the secant stiffness associate with relative drift at 80% pre-strength, increased, on average, from 21.8 kip/in. to 48.9 kip/in., which was nearly a 125% increase. The drift capacity of the cripple wall also increased. Looking at the 80% pre-strength relative drift, relative drift at strength, and the relative drift at 40% residual strength, the existing specimen had relative drift values of 1.4%, 2.4%, and 7.7%, respectively, on average considering both directions of loading. These same values were 2.2%, 5.5%, and 9.6% for the retrofitted counterpart. The range between the relative drift at 80% pre-strength and 40% residual strength increased from 6.3% to 9.7%.

In terms of improvement to the drift capacity, the 2-ft-tall cripple walls with stucco over framing exterior finishes saw the most improvement with Specimen A-17 versus Specimen A-18. The existing specimen reached 80% strength by 0.6% relative drift and 40% residual strength by

4.7% relative drift. With the addition of the retrofit, the specimen reached 80% strength by 1.3% relative drift, and 40% residual strength by 9.3% relative drift. Along with a dramatic increase to the drift capacity, the retrofit provided a 227% increase in lateral strength, with 557 plf on average between both loading directions for the existing specimen and 1815 plf on average for the retrofitted specimen. The initial secant stiffness increased from 52.5 kip/in. to 71.5 kip/in., a 36% increase, which is significant considering how the initial stiffness of the existing stucco specimen.

For the 6-ft-tall cripple walls with stucco exterior finishes, the strength per linear increased from 645 plf on average to 1814 plf for a 181% increase. The drift capacity increased as well but to lesser degree compared to the 2-ft-tall specimens. The 6-ft-tall stucco specimens experienced the smallest relative increase in initial stiffness. The initial secant stiffness was 20.5 kip/in. on average for the existing specimen and 32.2 kip/in. for the retrofitted specimen, a 57% increase. The lateral strength between the retrofitted 2-ft-tall and 6-ft-tall specimens were nearly identical on average considering both directions of loading: 1815 plf for the 2-ft-tall cripple wall and 1814 plf for the 6-ft-tall cripple wall.

For the specimens with stucco over diagonal sheathing exterior finishes—Specimen A-15 and Specimen A-16—the average strength per linear foot increased from 1027 plf to 2200 plf for a 116% increase. This was the lowest relative increase in strength. It is worth noting, however, the stucco over diagonal sheathing was the strongest material combination, with both the existing and retrofitted specimens were stronger than any of the other cripple walls with the same retrofit condition. The addition of the retrofit provided the largest increase in initial secant stiffness of any of the retrofitted specimens, from 48.1 kip/in. on average to 99.6 kip/in. (107% increase). The drift capacity did, however, reduce with the addition of the retrofit. Because both of these cripple walls experienced anchor bolt fractures and cracks in the sill plate, it cannot be said that the reduction in drift capacity would occur had the tests been repeated.

Once strength occurred, the retrofitted cripple walls experienced fairly consistent incremental drops in load at subsequent displacement cycles as the nails fastening the plywood panels to the interior framing would either pull out of the framing or tear through the plywood. Overall, failure of the cripple walls occurred when multiple edges of the plywood panels had detached from the framing. A more in-depth look at the damage characteristics and failures of the retrofitted cripple walls is provided in Chapter 4.

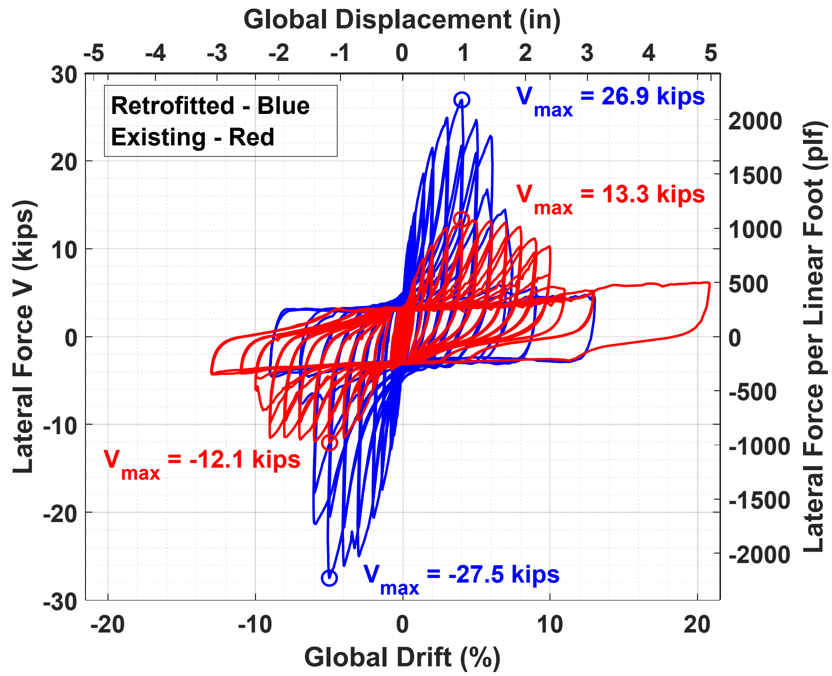


Figure 3.80 Specimens A-15 and A-16 comparison of *global* drift versus lateral load hysteretic response for retrofitted and existing 2-ft-tall cripple walls with stucco over diagonal sheathing exterior finish and bottom boundary condition "d".

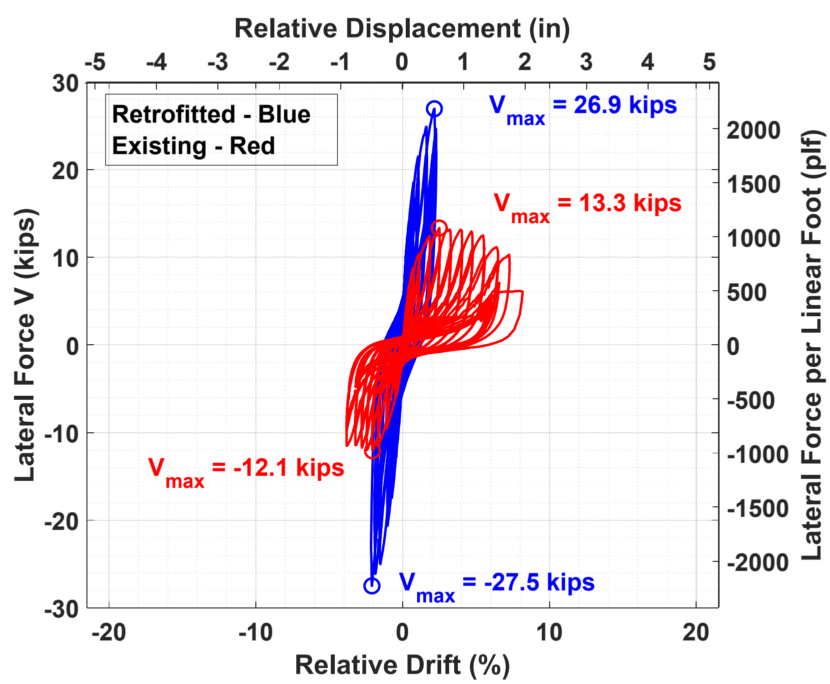


Figure 3.81 Specimens A-15 and A-16 comparison of *relative* drift versus lateral load hysteretic response for retrofitted and existing 2-ft-tall cripple walls with stucco over diagonal sheathing exterior finish and bottom boundary condition "d".

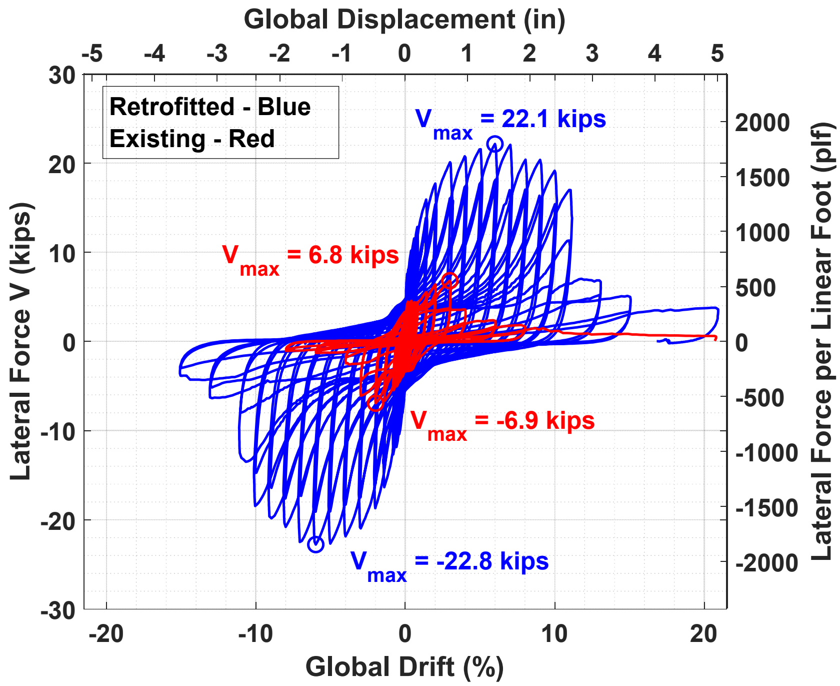


Figure 3.82 Specimens A-17 and A-18 comparison of *global* drift versus lateral load hysteretic response for retrofitted and existing 2-ft-tall cripple walls with stucco exterior finish and bottom boundary condition "d".

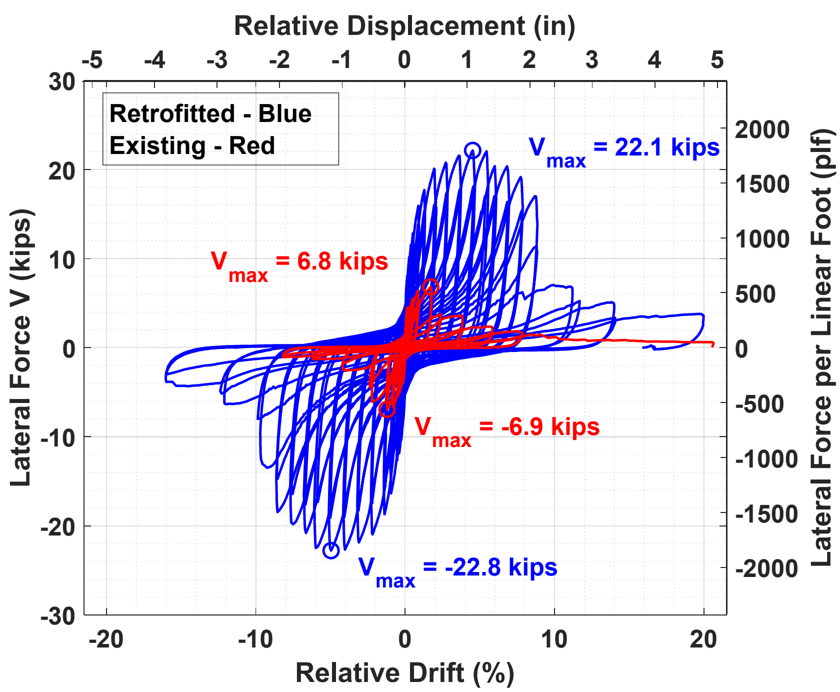


Figure 3.83 Specimens A-17 and A-18 comparison of *relative* drift versus lateral load hysteretic response for retrofitted and existing 2-ft-tall cripple walls with stucco exterior finish and bottom boundary condition "d".

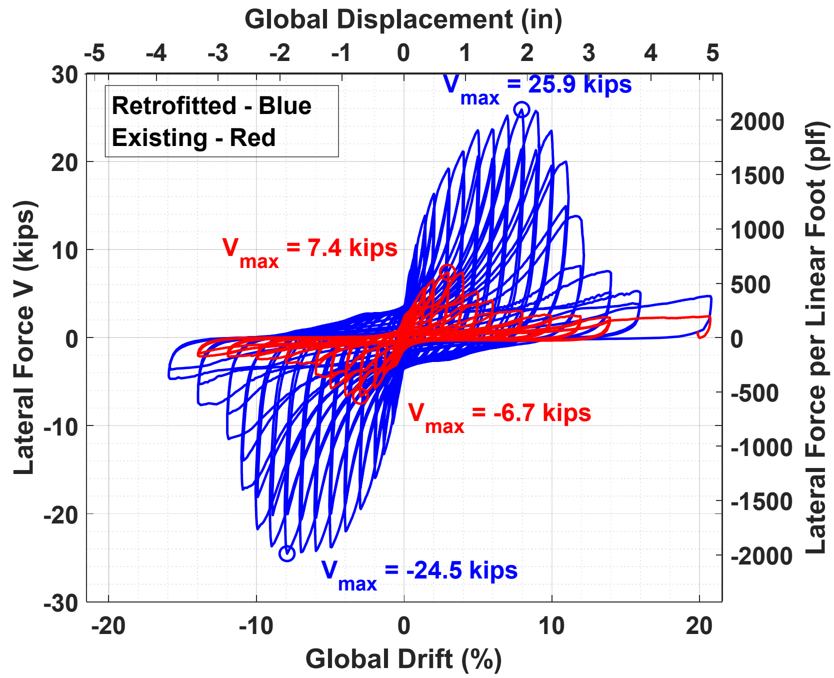


Figure 3.84 Specimens A-20 and A-19 comparison of *global* drift versus lateral load hysteretic response for retrofitted and existing 2-ft-tall cripple walls with stucco over horizontal sheathing exterior finish and bottom boundary condition "c" (retrofitted) and d (existing).

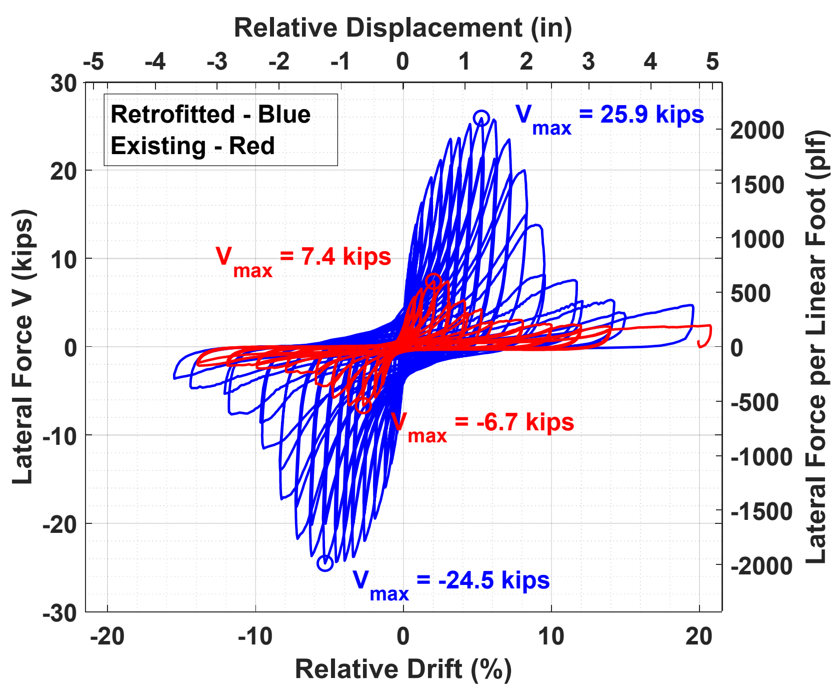


Figure 3.85 Specimens A-20 and A-19 comparison of *relative* drift versus lateral load hysteretic response for retrofitted and existing 2-ft-tall cripple walls with stucco over horizontal sheathing exterior finish and bottom boundary condition "c" (retrofitted) and d (existing).

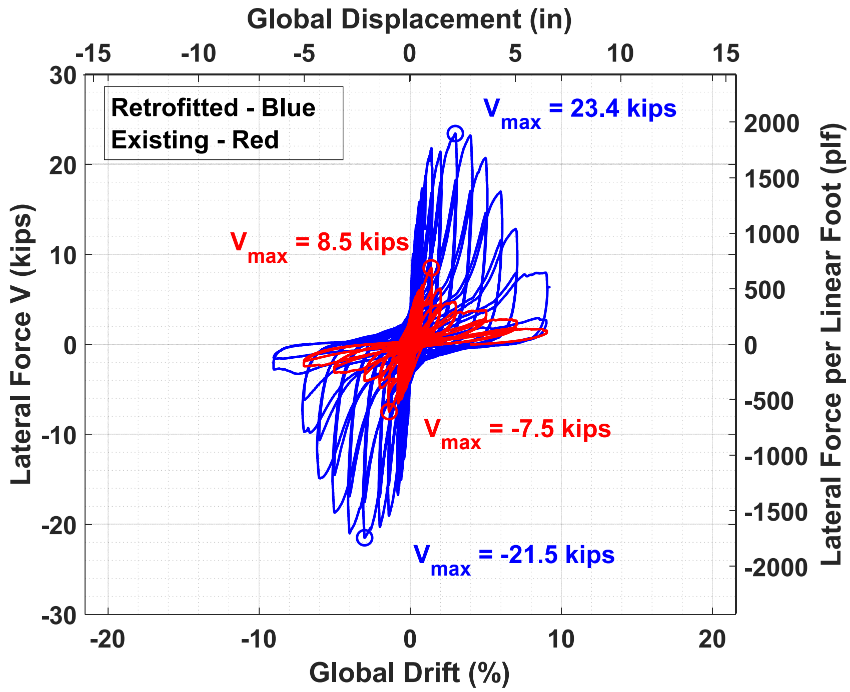


Figure 3.86 **Specimens A-25 and A-26 comparison of *global* drift versus lateral load hysteretic response for retrofitted and existing 6-ft-tall cripple walls with stucco exterior finish and bottom boundary condition "c".**

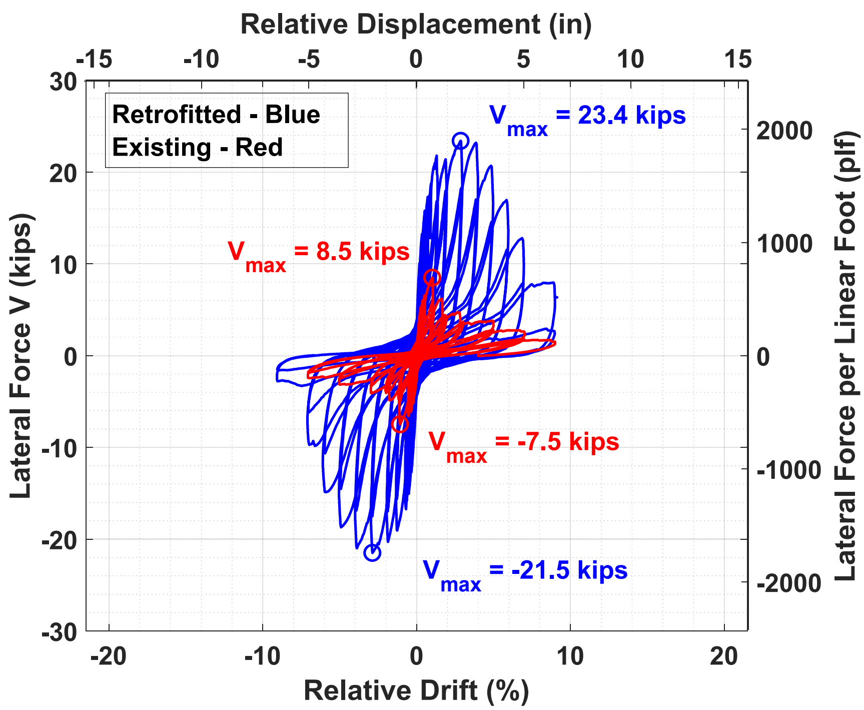


Figure 3.87 **Specimens A-25 and A-26 comparison of *relative* drift versus lateral load hysteretic response for retrofitted and existing 6-ft-tall cripple walls with stucco exterior finish and bottom boundary condition "c".**

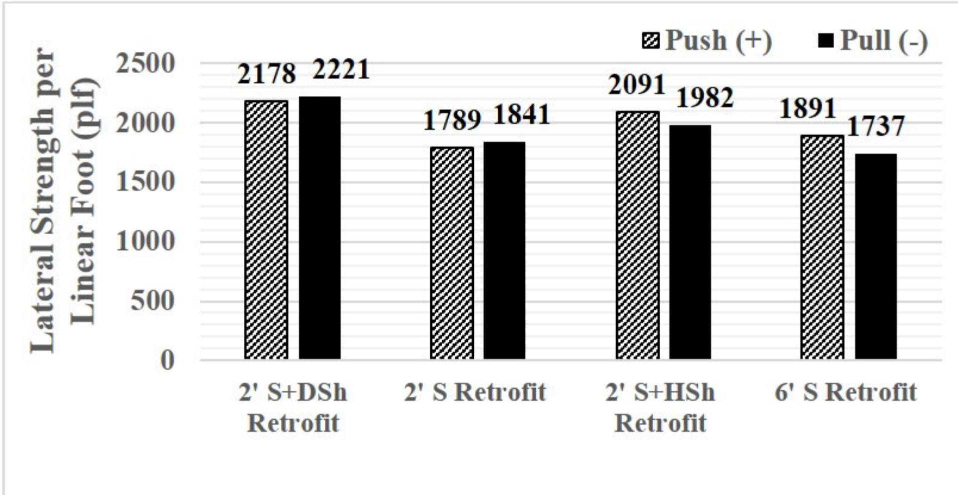


Figure 3.88 Lateral strength per linear foot for all retrofitted stucco specimens.

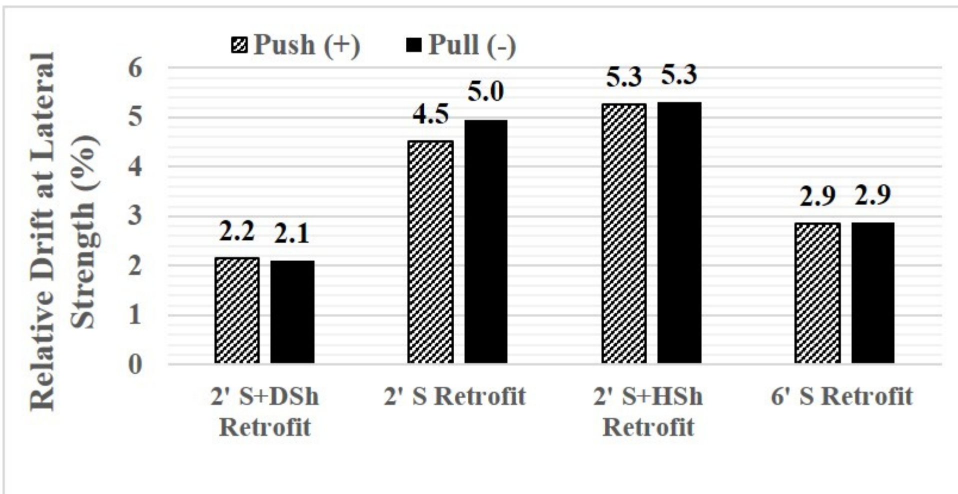


Figure 3.89 *Relative* drift at lateral strength for all retrofitted stucco specimens.

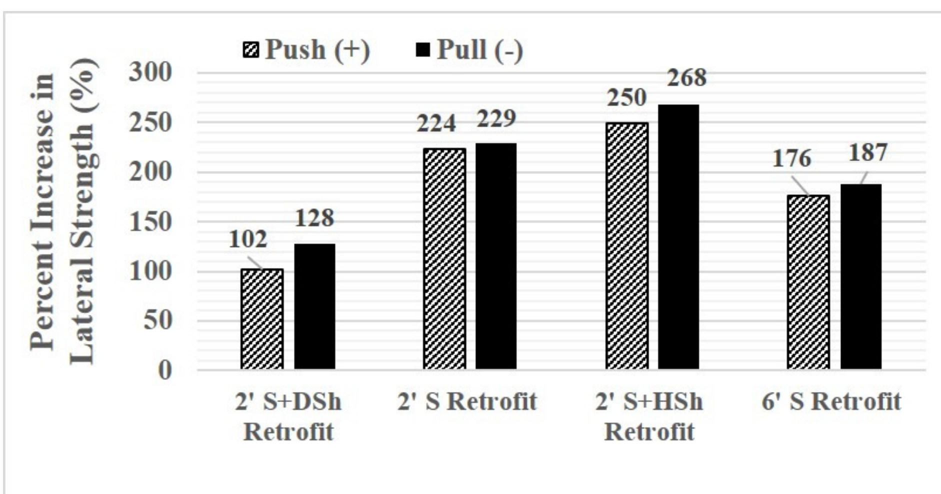


Figure 3.90 Contribution of retrofit to lateral strength for all retrofitted stucco specimens.

3.8 ENVELOPES OF HYSTERETIC RESPONSE

It is useful to cross the response of the cripple walls using overlays of the envelopes extracted from the lateral force–lateral displacement hysteresis. These curves were obtained by extracting the strength at each drift amplitude throughout the loading protocol. It is noted that only the leading cycles of each cycle group were considered. Figures 3.91 to 3.96 show key comparisons of the cripple walls using the envelopes of each specimen's hysteresis. Both the push and pull loading is displayed in the same quadrant for ease of comparison.

Figure 3.91 compares existing 2-ft-tall cripple walls with the three wet exterior finishes. While the strength of the stucco over framing finished and stucco over horizontal sheathing specimens were similar, they were significantly lower in strength than the stucco over diagonal sheathing finish. The strength of the stucco over diagonal sheathing finished cripple wall was 75% higher than the stucco over horizontal sheathing finished cripple wall, and 85% higher than the stucco over framing finished cripple wall. The stucco over horizontal sheathing provided a 6% increase in strength compared with the stucco finished specimen.

The most symmetric response came with the stucco finished specimen. This cripple wall also achieved strength earlier than either of the other cripple walls. The stucco over diagonal sheathing had the largest drift capacity of all the other exterior finishes. It is interesting to note that the stucco over diagonal sheathing achieved higher strength in the push loading direction than in the pull loading direction. With a diagonal sheathing finish, it would have been expected that the strength in the pull direction was greater than the strength in the push direction due to the orientation of the sheathing boards. When tested, the gaps between the boards would expand during push loading and contract during pull loading. Once the gaps between the boards had fully closed, the cripple wall would gain additional strength due to the sheathing boards bearing on one another. However, this did not occur with the stucco over diagonal sheathing finished specimen due to a cross-grain split propagating across the entire still plate before the required displacement was achieved to have the bearing condition of the sheathing boards. The stucco over framing and stucco over diagonal finished sheathing cripple walls had similar stiffnesses, while the stucco over horizontal sheathing finished cripple wall was more flexible.

In Figure 3.92, the envelopes of the global drift versus lateral strength are shown for the retrofitted 2-ft-tall specimens with the three wet exterior finishes. The comparative response of the three walls was similar to their existing counterparts, with the exception of the stucco over diagonal sheathing specimen that lost strength much earlier than the existing specimen. Recall that this specimen failed due to fractures of all seven anchor bolts, which is why the response shows such a brittle failure. If the anchor bolts had stayed intact, then it would be expected that the cripple wall would have continue to gain strength in later displacement cycles with a more distinguishable difference between the response in the push and pull direction of loading. The strength of the stucco over diagonal sheathing cripple wall was 22% higher than the stucco-only cripple wall and 9% higher than the stucco over horizontal sheathing cripple wall, which is a large difference compared to the existing cripple walls. The stucco over horizontal sheathing and stucco over framing finished cripple walls had similar responses up to the 6% global drift ratio; past that point the stucco over horizontal sheathing specimen continued to gain strength while the stucco over framing specimen began to lose strength.

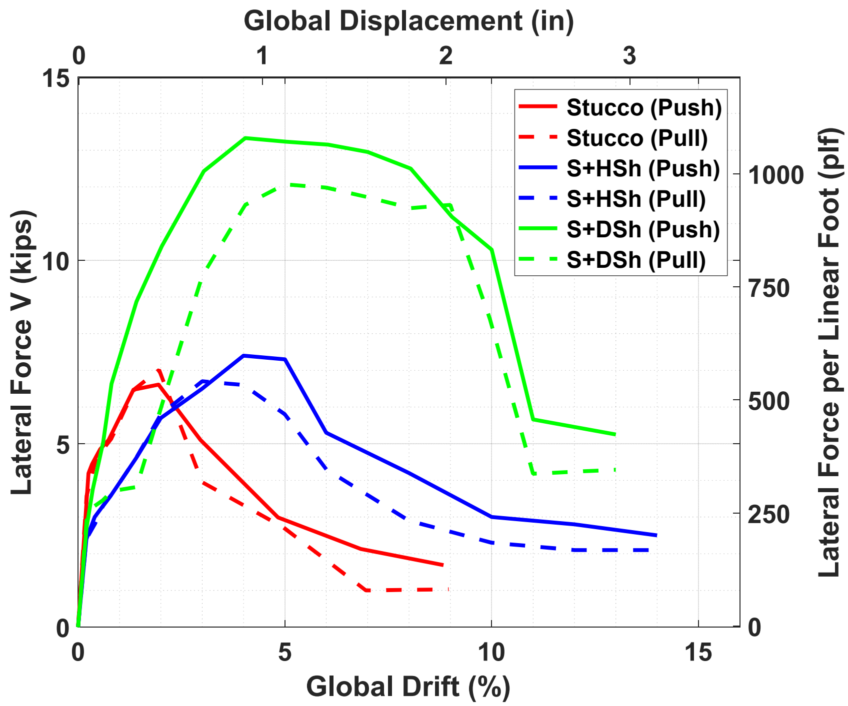


Figure 3.91 Comparison of envelopes of ***global*** drift versus lateral strength hysteretic response for finish materials (existing).

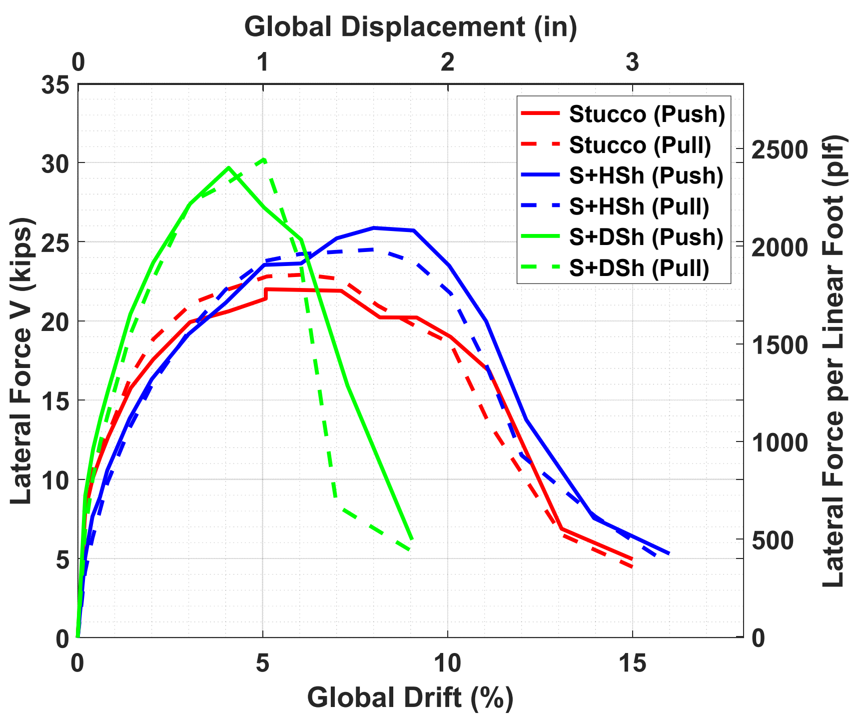


Figure 3.92 Comparison of envelopes of ***global*** drift versus lateral strength hysteretic response for finish materials (retrofit).

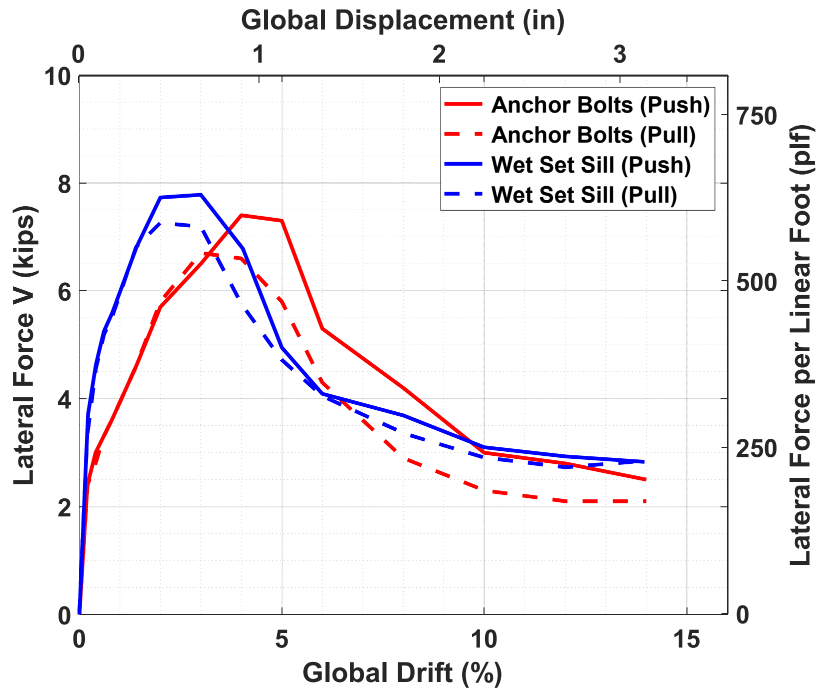


Figure 3.93 **Comparison of envelopes of *global* drift versus lateral strength hysteretic response for type of anchorage.**

Figure 3.93 compares the envelopes for the two types of anchor conditions. Both cripple walls were existing 2-ft-tall specimens with stucco over horizontal sheathing exterior finishes. One of the cripple walls had a typical sill plate fastened with anchor bolts at 64 in. on center while the other had a wet set plate. The wet set sill plate reached a higher strength (7% increase) and reached strength sooner than the typical sill plate specimen. The specimen with the wet set sill plate had no displacement of the sill plate relative to the foundation, while the typical sill plate specimen had around 0.6% sill relative drift at strength. In terms of the relative response, the two specimens achieved strength at the same time for an average of 2.5% relative drift between both directions of loading. The wet set sill plate specimen provided a 37% increase in initial secant stiffness. The initial secant stiffness is defined as the secant stiffness associated with relative drift at 80% pre-strength.

Comparisons of the envelopes of global drift versus lateral strength for stucco over framing finished cripple walls with different heights (2-ft-tall and 6-ft-tall) are shown in Figures 3.94 to 3.95. Figure 3.94 shows the response of the existing cripple walls. Initially the responses of both walls were identical; however, after 0.4% global drift, the 6-ft-tall specimen began to gain more strength compared to the 2-ft-tall specimen. The lateral strength of the 6-ft-tall specimen was 16% higher than that of the 2-ft-tall specimen, but the initial secant stiffness decreased by 61%. Both cripple walls experienced significant drops of load in subsequent drift cycles after reaching strength. With stucco over framing finished specimens, once the strength was achieved, the stucco detached from the furring nails at the sill plate and continued to detach to the furring nails running up the length of the studs, causing a rapid, large drop in strength once it after reaching strength. This reduction in strength was greater for the taller specimen as the imposed displacements were three times that of the shorter specimen.

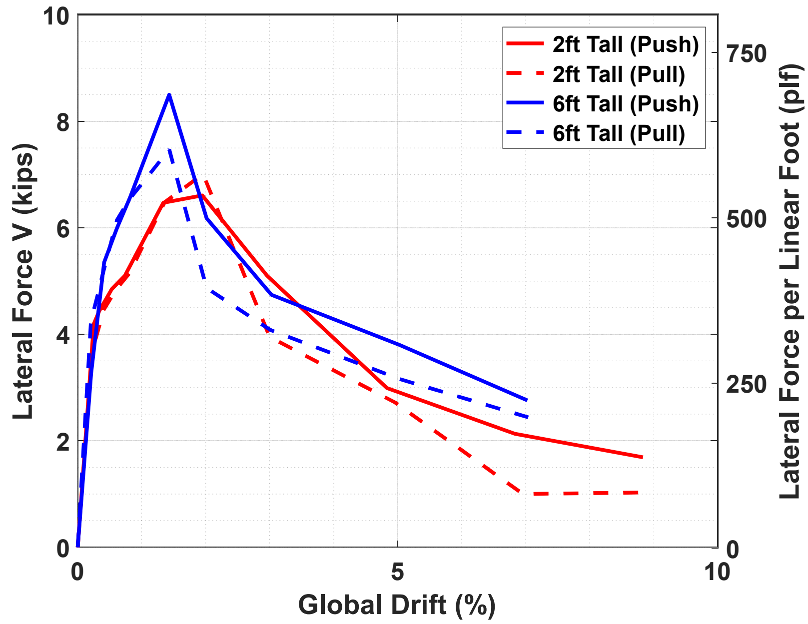


Figure 3.94 Comparison of envelopes of ***global*** drift versus lateral strength hysteretic response for the existing stucco finished 2-ft-tall and 6-ft-tall cripple walls.

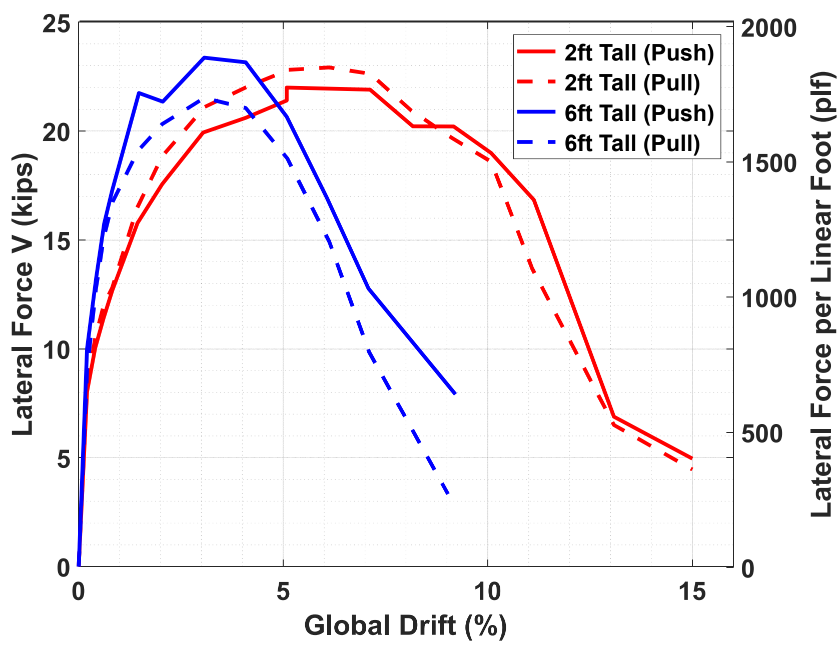


Figure 3.95 Comparison of envelopes of ***global*** drift versus lateral strength hysteretic response for the stucco finished retrofitted stucco finished 2-ft-tall and 6-ft-tall cripple walls.

Figure 3.95 compares the envelopes of global drift versus lateral strength hysteretic response for the retrofitted specimens. The strength of both specimens was nearly identical – 1814 plf on average between both loading directions for the 6-ft-tall specimen and 1815 plf for the 2-ft-tall specimen. Strength was achieved earlier for the taller specimen than the shorter due to the shorter specimen having increased displacement between the sill plate and the foundation compared with the taller specimen. In terms of the relative response, the 6-ft-tall specimen reached strength at 1.1% relative drift while the 2-ft-tall specimen reached strength at 1.5% relative drift on average between both directions of loading. This is more comparable than the global response where these were 3% global drift for the 6-ft-tall specimen and 6% global drift for the 2-ft-tall specimen. The most significant difference in the response was the stiffness of the two specimens. It is expected that a taller wall will be more flexible than a shorter one, which was the case, as the initial secant stiffness increased by 122%.

Figure 3.96 shows the envelopes of global drift versus lateral strength hysteretic response for an existing 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish (Specimen A-20) as well as the monotonic response of an existing 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish (Specimen A-27). Specimen A-27 was the only cripple wall in this test program to be loaded monotonically. The details of this specimen were chosen based off the most commonly tested details in this program which are representative of some of the most common details that are found in California's housing stock. Besides loading protocol, the two cripple walls differ in their boundary condition at the bottom of the walls. Specimen A-20 had an extension of the stucco down the footing which was not present for Specimen A-27. As discussed in Section 3.2, the response of the walls was not affected by this change in boundary condition due to damage to the bond between the stucco and the footing that were sustained during transportation of the specimen into the testing apparatus. The strength per linear foot of the monotonically loaded specimen was 715 plf compared with 569 plf for the cyclically loaded specimen (26% increase). The monotonically loaded specimen achieved strength at larger displacement amplitudes than the cyclically loaded specimen as well (6% global drift versus 3% global drift). The relative drift at 80% pre-strength was 2% versus 1.4%, at strength was 5.4% versus 2.4%, and at 40% residual strength was 9.7% versus 7.7%, for the monotonic versus the cyclic specimen. The increase in strength and drift capacity demonstrated that the attachment of the stucco to the furring nails were degraded by the cyclic loading. At large drift amplitudes (11–14% global drift ratio), the two cripple walls had a similar response. At that point, the stucco no longer provided much resistance, and the majority of the strength comes from the horizontal sheathing.

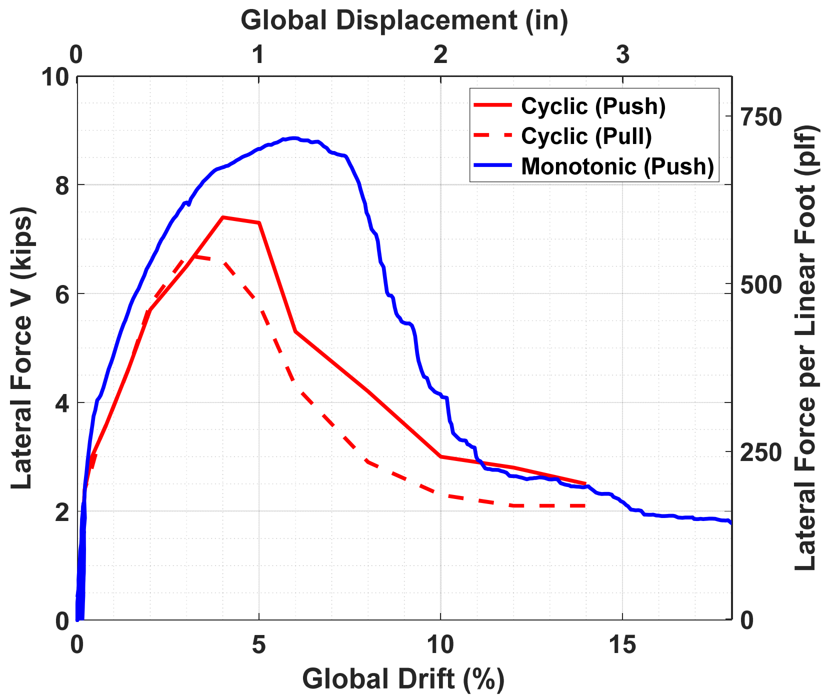
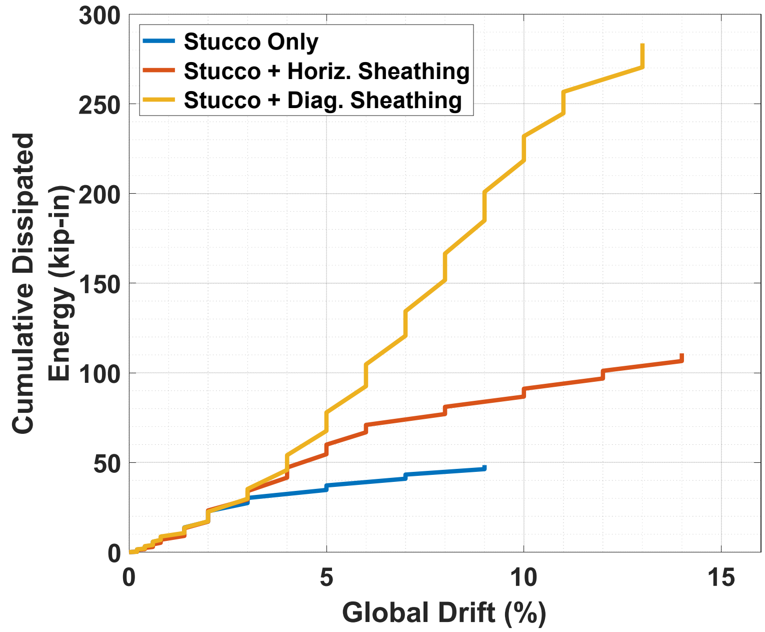


Figure 3.96 **Comparison of envelopes of *global* drift versus lateral strength; hysteretic response and monotonic response for the existing stucco over horizontal sheathing finished 2-ft-tall cripple walls.**

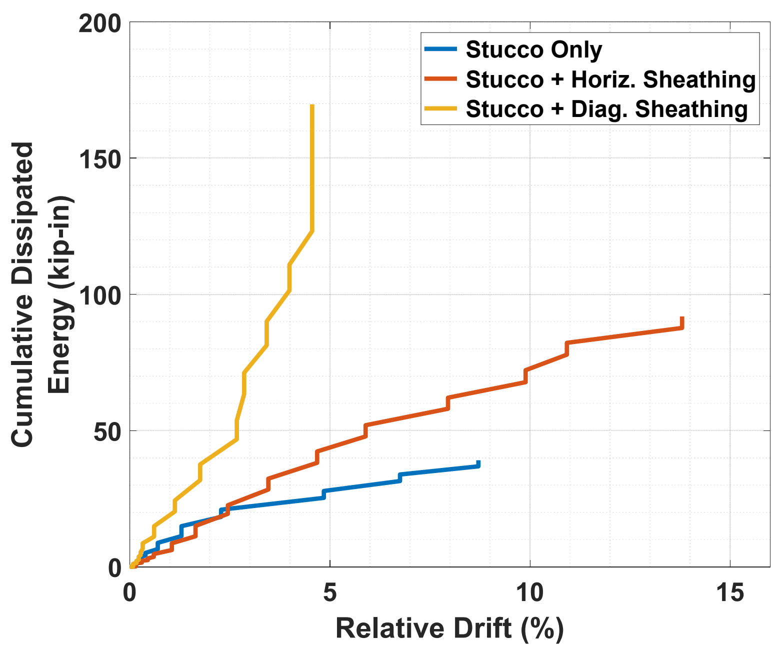
3.9 HYSTERETIC ENERGY DISSIPATION

An important characteristic used to describe the seismic resiliency of a cripple wall is the energy dissipated by the cripple wall during loading. Figures 3.97 through 3.100 compare the cumulative energy dissipated versus drift for both the 2-ft- and 6-ft-tall cripple walls. 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 3.97 compares the cumulative energy dissipated for existing 2-ft-tall cripple walls tested. The three walls varied in their exterior finishes: stucco over framing, stucco over horizontal sheathing, and stucco over diagonal sheathing. Up to 3% global drift, the hysteretic energy dissipation was nearly equal for all specimens, showing that the furring nails fastening the stucco provided most of the energy dissipation. After this point, the stucco over diagonal sheathing finished specimen began dissipating more energy than the other two cripple walls. By 8% global drift, the stucco over diagonal sheathing finished specimen has dissipated 220% more energy than the stucco only finished specimen, and over 100% more energy than the stucco over horizontal sheathing finished specimen. The stucco over horizontal sheathing finished specimen had dissipated over 50% more energy than the stucco only finished cripple wall. At the 8% global drift ratio, the cyclic portion of the test had concluded for the stucco-only finished specimen; therefore, it is used as a point of comparison. In Figure 3.98, the comparison is made for the retrofitted counterparts of the specimens discussed in the previous figure. From the global response, the energy dissipated was nearly the same for all three cripple walls. It should be noted that much of the imposed displacement for the stucco over diagonal sheathing cripple wall came from displacement of the sill plate relative to the foundation. When looking at the relative response, the energy dissipation is also nearly the same up to 2% relative drift. At this point, the stucco over diagonal sheathing specimen decreased in relative drift for subsequent drift cycles due to increased displacements occurring between the sill plate and the foundation instead of the actual cripple wall. The stucco-only finished specimen and stucco over horizontal sheathing finished specimen dissipated nearly the same amount of energy up to 3.5% relative drift. After this point, the specimen with sheathing began dissipating more energy than the specimen without. Had there not been fractures to the anchor bolts for the stucco over diagonal sheathing specimen, it would have been expected that this cripple wall would have dissipated more energy compared to the other two.

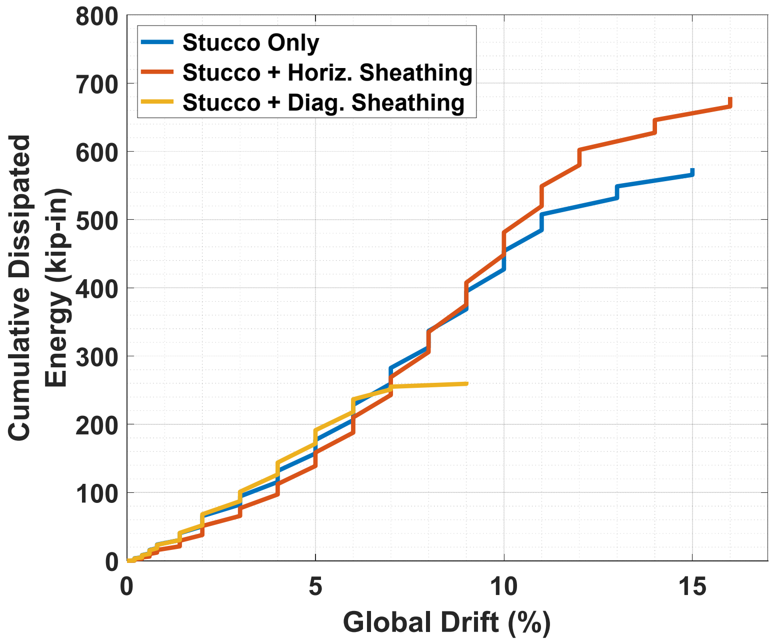


(a)

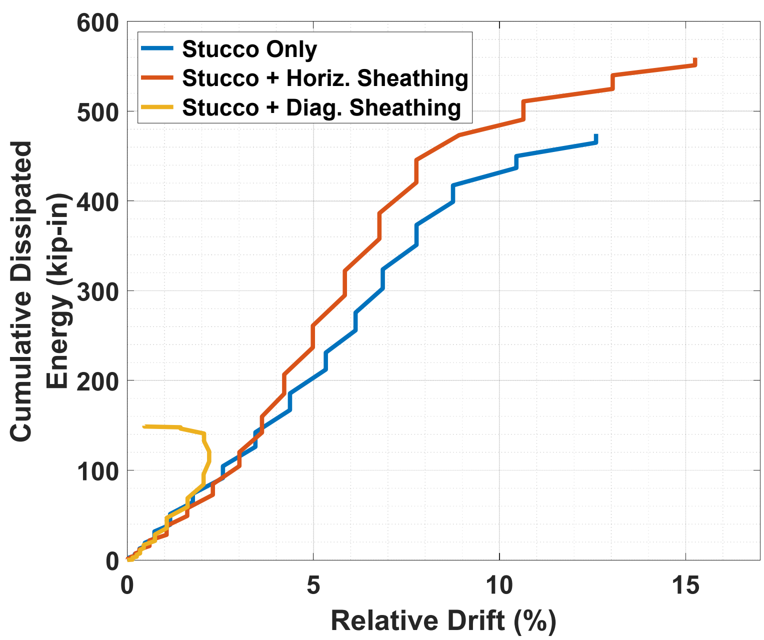


(b)

Figure 3.97 **Comparison of the existing of the hysteretic energy dissipation for the existing 2-ft-tall cripple wall: (a) *global* response; and (b) *relative* response.**



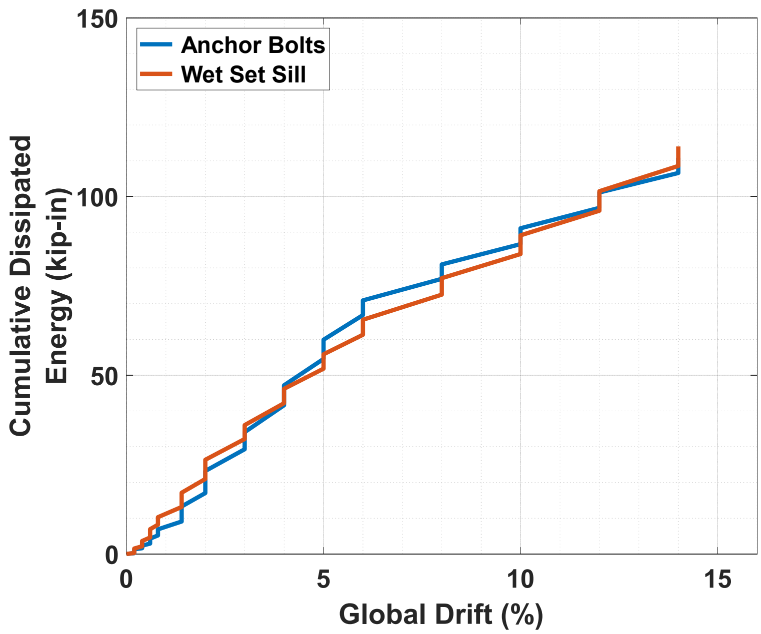
(a)



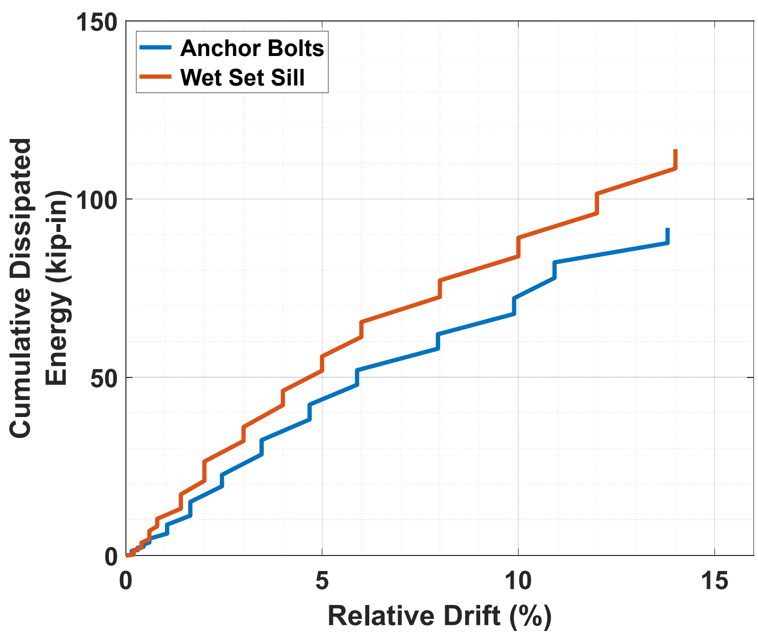
(b)

Figure 3.98 Comparison of the existing of the hysteretic energy dissipation for the retrofitted 2-ft-tall cripple wall: (a) *global* response; and (b) *relative* response.

Figure 3.99 compares the energy dissipated for existing 2-ft-tall cripple walls with stucco over horizontal sheathing exterior finishes that differed in their anchorage condition. A look at the global response shows that the energy dissipation is nearly equal over the entire test for the two specimens. Considering the relative response, the wet set sill specimen dissipated almost 25% more energy than the specimen with the typical anchorage condition. Displacement of the sill plate relative to the foundation energy dissipated to overcome the frictional resistance between the sill plate and the foundation. In the case of the specimen with the typical anchorage, this accounted for almost 25% of the energy dissipated.



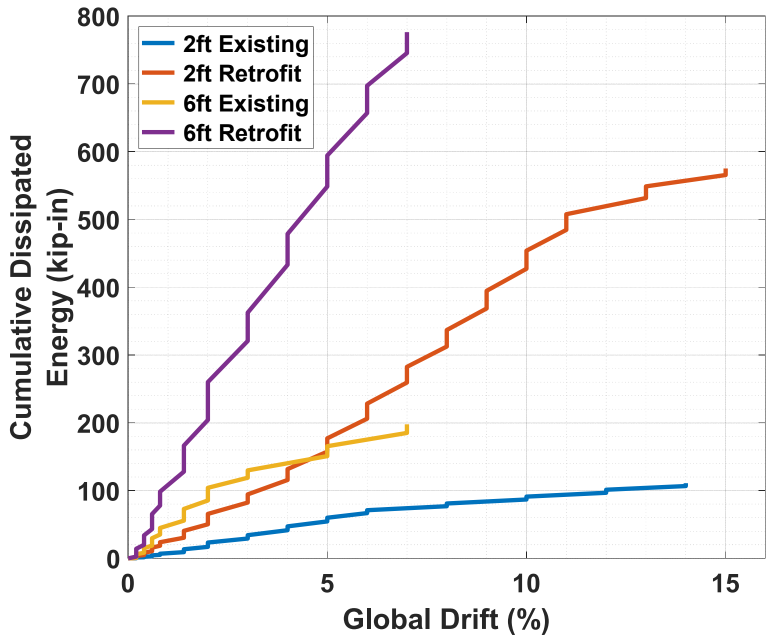
(a)



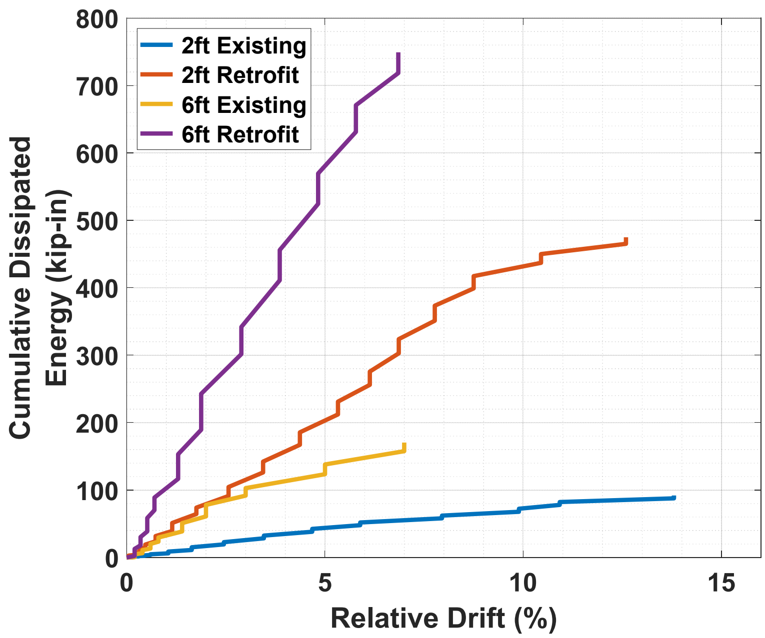
(b)

Figure 3.99 Anchorage condition hysteretic energy dissipation comparison: (a) *global* response; and (b) *relative* response.

Figure 3.100 compares the energy dissipated of the and retrofitted 2-ft-tall and 6-ft-tall cripple walls with stucco over framing finish. For both the existing and retrofitted cases, the 6-ft-tall cripple walls dissipated more energy than their 2-ft-tall counterparts. The amount of energy dissipated for the existing 6-ft-tall cripple walls was 270% higher than the 2-ft-tall specimen at 3% global drift, which is where the loading protocol diverged. The increased energy dissipation is largely due to the amount of displacement imposed on the 6-ft-tall specimens being three times higher compared to the 2-ft-tall specimens, the increased number of fasteners attaching the stucco to the framing, and the 6-ft-tall specimen achieving strength earlier than the 2-ft-tall specimen. The added retrofit accounted for a nearly a 700% increase in the energy dissipated by 10% global drift for the 2-ft-tall cripple walls and over an 850% increase for the 6-ft-tall cripple walls. Horizontal siding had by far the lowest capacity of any of the dry exterior finishes; therefore, the added retrofit would naturally provide large increases in the amount of energy dissipated. At the final drift amplitude before the loading protocols diverged, the retrofitted specimen had dissipated 385% more energy than the existing specimen @ 6% global drift for the 2-ft-tall cripple walls. For the 6-ft-tall cripple walls, the retrofitted specimen had dissipated 175% more energy than the existing specimen @ 3% global drift).



(a)



(b)

Figure 3.100 **Comparison of the hysteretic energy dissipation for the existing and retrofitted 2-ft- and 6-ft-tall cripple walls with stucco exterior finish: (a) *global* response; and (b) *relative* response.**

3.10 RESIDUAL DRIFT

As the cripple walls were cyclically loaded, they accumulated residual deformation. Residual deformation is an effective tool to evaluate the structural performance of a cripple wall under seismic excitation. In addition, residual deformation represents the final state of a structure after an earthquake, thus making it a concern for homeowners as the aesthetic and structural performance of the dwelling are both affected.

The residual displacement of the cripple walls was measured at the end of each displacement cycle level and can be defined as the amount of displacement in the cripple wall measured when there is no lateral force being imposed on the cripple wall. As the amplitude of the displacement increased, the residual displacement increased to the point where it became visible, even prior to the cripple walls achieving full strength. Figure 3.101 shows the global residual displacement of the cripple walls after the 1.4% drift cycle group. Global residual displacement refers to not only the residual displacement of the cripple wall itself but also to the residual displacement of the sill plate relative to the foundation. Figure 3.102 shows the relative residual displacement of the cripple walls after the 1.4% drift cycle group. The relative residual displacement accounts for only the deformation sustained in the cripple wall, excluding any deformation of the sill plate relative the foundation. For convenience, the relative residual displacement will be referred to as residual displacement.

This measurement is a better indicator of the structural performance of the cripple wall as it only accounts for the residual deformation of the cripple wall. There were variations in the alignment of the sill plate connection to the foundation as the anchor bolt holes were oversized by 1/4 in. It should be noted that the residual displacements were not normalized by any height metric within Figures 3.101 through 3.105. Naturally, the 6-ft-tall cripple walls would have more residual displacement than their 2-ft-tall counterparts due to the imposed displacement being three times as much for the 6-ft-tall cripple walls than the 2-ft-tall cripple walls.

For 2-ft-tall cripple walls, the global residual displacement was between 0.16–0.28 in. or 0.6%– 1.2% drift; see Figure 3.101. The largest global residual displacement was for Specimen A-15 with a stucco over diagonal sheathing finish. There was little difference between the global residual displacement for the existing and retrofitted cripple walls. For the 6-ft-tall cripple walls, the global residual displacement ranged from 0.38–0.42 in. or 0.5%–0.6% drift. In terms of global residual displacement as a percentage drift, the height of the cripple wall had little effect on the residual displacement. When looking at the residual displacement at 1.4% global drift shown in Figure 3.102, most cripple walls experienced reductions in their residual drift compared to their global residual drift. The cripple walls with stucco over diagonal sheathing had dramatic differences between the global residual displacement and the residual displacement, decreasing from 0.28 and 0.24 in. to 0.02 and 0.11 in. This was caused by the large amounts of displacement that accrued between the sill plate and the foundation as the cripple wall slid along the foundation instead of the wall itself deforming. This figure also indicates the relative drift of the cripple walls at 1.4% global drift.

It is more useful to compare the residual displacements in the cripple walls at the same relative drift amplitude. If a linear interpolation is performed to determine the residual displacement at 1.4% relative drift, the residual displacements were much more consistent, as shown in Figure 3.103. For the 2-ft-tall specimens, the range in residual displacement was 0.13–

0.25 in. (0.5%–.0% drift), and for the 6-ft-tall specimens, the range was 0.40–0.48 in. (0.6%–0.7% drift). The stucco finished specimen had the largest amount of residual drift (0.19–0.25 in.) and the stucco over diagonal sheathing specimen (0.13–0.19 in.). Overall, the diagonal sheathing finish material behaved more elastically than the other finish materials, which is likely attributed to the orientation of the diagonal sheathing that provided increased lateral resistance.

Figure 3.106 shows the global residual displacement at strength. Since the strengths occurred over a wide range of drifts and the amount of sill plate to foundation displacement varied drastically between specimens, there were not as many decipherable trends between the walls. In Figure 3.105, the residual displacement is shown at strength. The existing specimens with stucco finishes had nearly the same residual displacement (0.17 and 0.18 in. @ ~0.7% drift). In general, the stucco-only finished specimens had the least residual drift at strength, followed by the stucco over diagonal sheathing finished specimens, and lastly, the stucco over horizontal sheathing finished specimens. There was a reduction in the residual displacement of the stucco over diagonal sheathing due to the fractures of the anchor bolts and splitting of the sill plate.

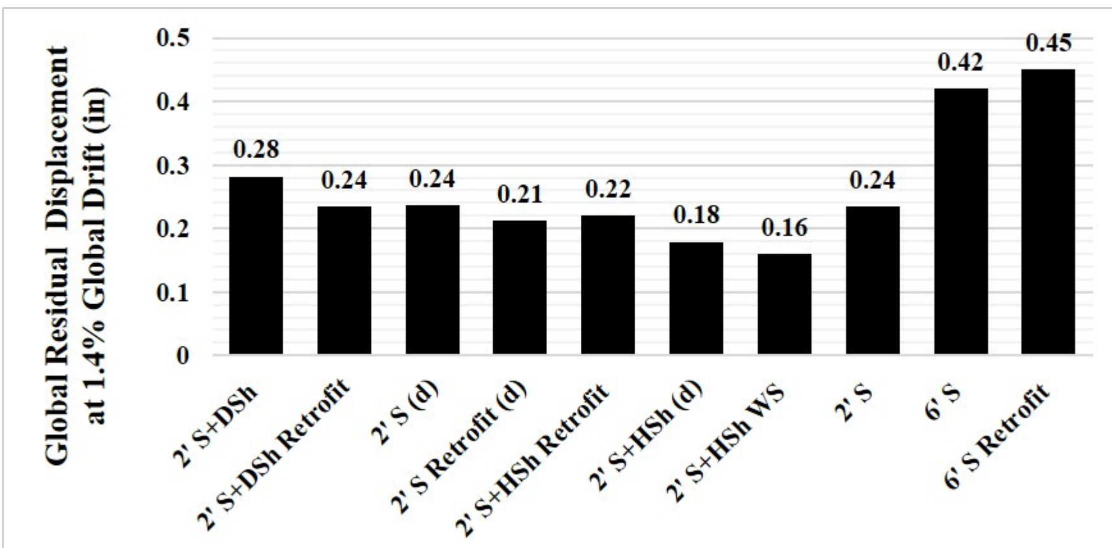


Figure 3.101 ***Global*** **residual displacement of cripple walls at the end of the 1.4% global drift cycle group.**

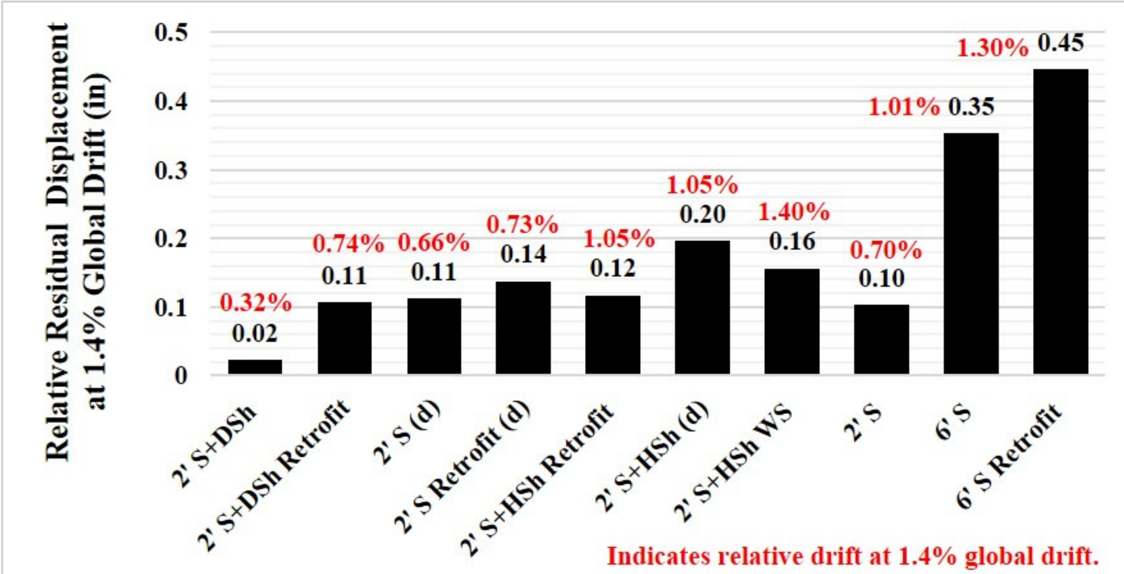


Figure 3.102 *Relative* residual displacement of cripple walls at the end of the 1.4% global drift cycle group.

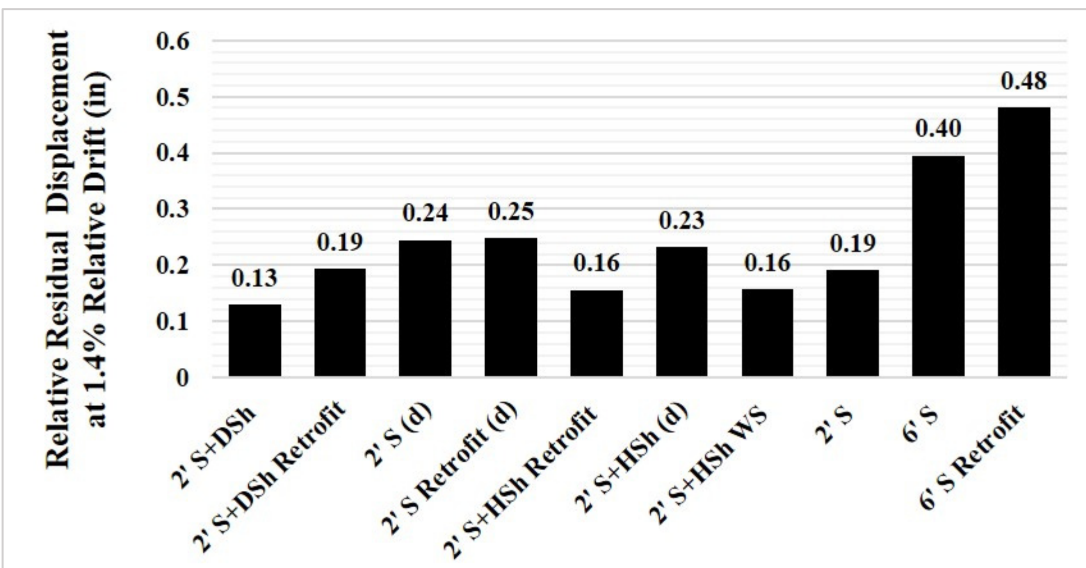


Figure 3.103 *Relative* residual displacement of cripple walls at the end of the 1.4% relative drift cycle, linearly interpolated.

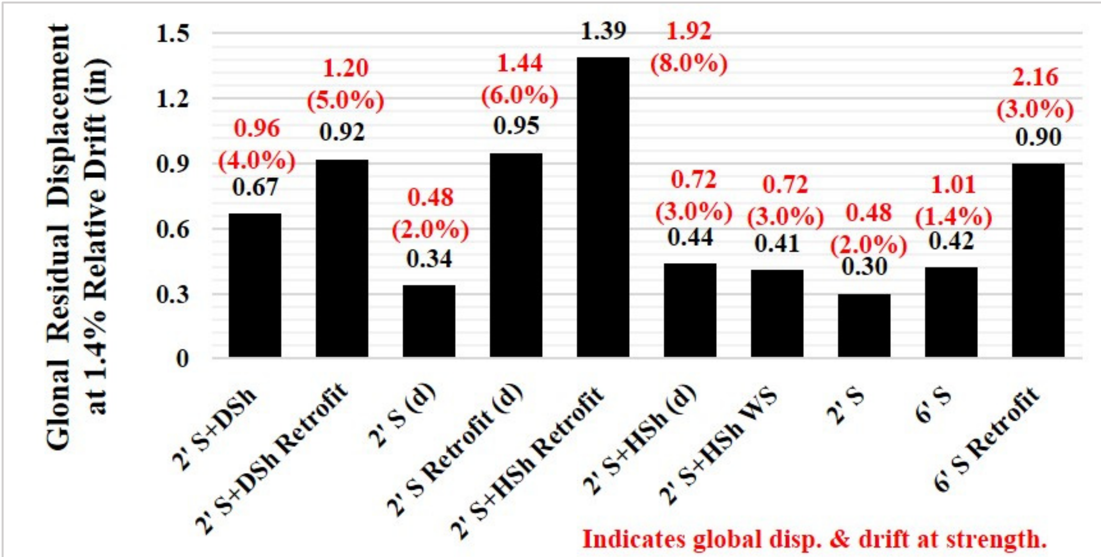


Figure 3.104 ***Global*** **residual displacement of cripple walls at the end of the peak strength drift cycle group.**

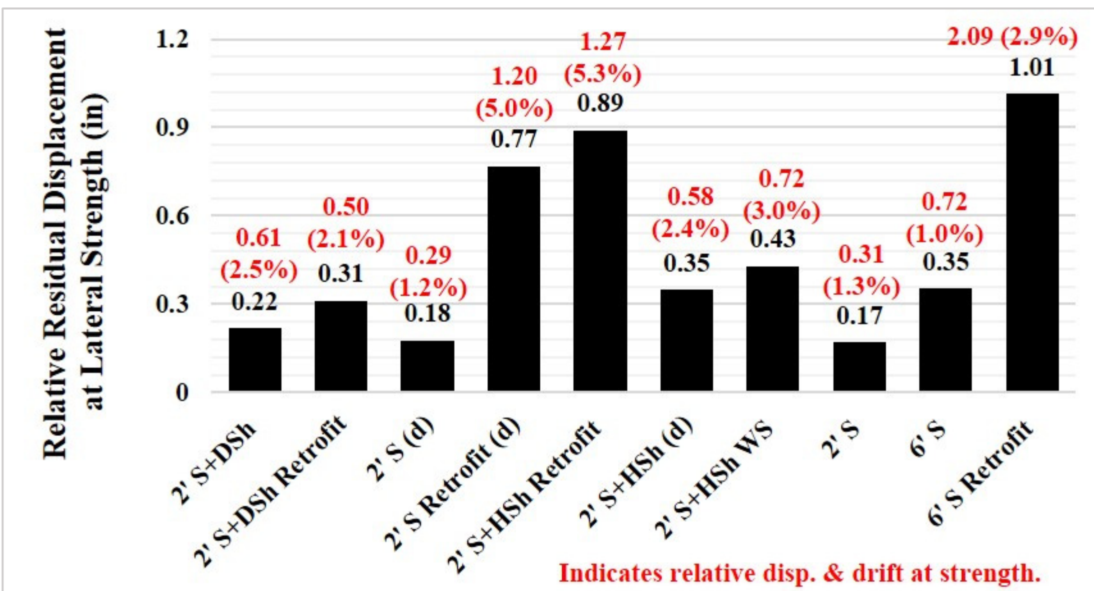


Figure 3.105 ***Relative*** **residual displacement of cripple walls at the end of the peak strength drift cycle group.**

3.11 VERTICAL LOAD

The vertical load was applied vertically with two 4 × 4 × 3/8-in. HSS members acting as point loads, using four hydraulic jacks connected to four rods. The hydraulic jacks used the ceiling of the strong floor as a reaction point. The load is measured with four axial load cells, one for each rod. The connection of the rods to the hydraulic jacks were only able to rotate, creating a pinned connection at the ceiling of the strong floor. As the cripple walls displaced, the applied load began to develop a horizontal component, which needed to be included in the actual horizontal force being applied to the cripple wall. Since the horizontal component opposed the measured lateral force, the corrected lateral force would be reduced by the measured lateral force. The vertical load experienced by the cripple wall was also reduced due to the displacement of the cripple wall but to a negligible degree. Figure 3.106 shows the set up for the application of the vertical load, and Figure 3.107 shows the geometry of the vertical load and lateral load as the cripple wall displaced. Overall, the correction for the lateral load was a reduction in the range of 0–3% for all cycles for the 2-ft-tall cripple walls and 0–6% for 6-ft-tall cripple walls. During the monotonic push, the correction would have a maximum reduction of around 5% for 2-ft-tall cripple walls and 10% for 6-ft-tall cripple walls. Note that all results presented have accounted for these corrections. The equation to for the corrected lateral load and corrected vertical load are as follows:

The vertical load for all specimens was 450 plf. The 450 plf load is representative of the weight of a two-story dwelling with heavy building materials. To achieve 450 plf of vertical load, 5 kips were applied between the four hydraulic jacks after the weight of the horizontal load transfer beam, laminated wood beam, and HSS sections had been accounted for. Throughout the displacement cycles, the vertical load applied by the jacks would oscillate. These oscillations are shown in Figure 3.108. For all cripple walls, the vertical loads fluctuated from by a range of 1.2 to 4.2 kips over their entire loading protocol. The maximum vertical load experienced was 2.9 kips by Specimens A-15 and A-19, and the lowest vertical load was 6.9 kips by Specimen A-19.

$$V_{actual} = V_{measured} - P_{rod}\sin(\theta_{rod}),$$

$$P_{actual} = P_{rod}\cos(\theta_{rod}), \text{ where } \theta_{rod} = \sin^{-1}\frac{\Delta}{L_{rod}}$$

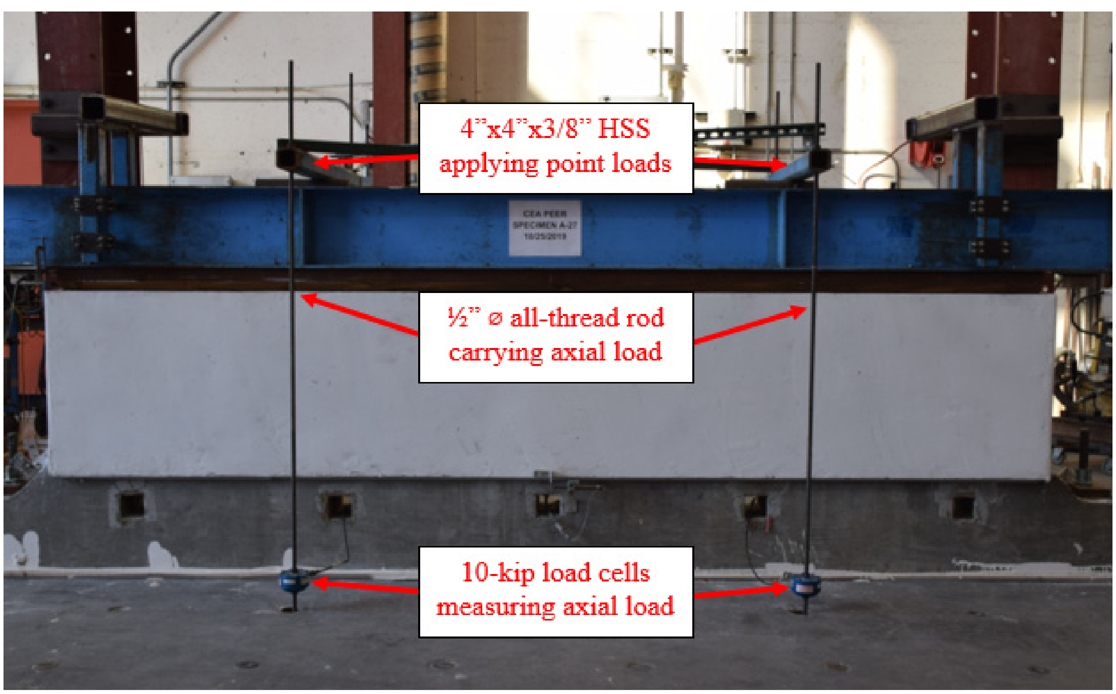


Figure 3.106 Vertical load set up.

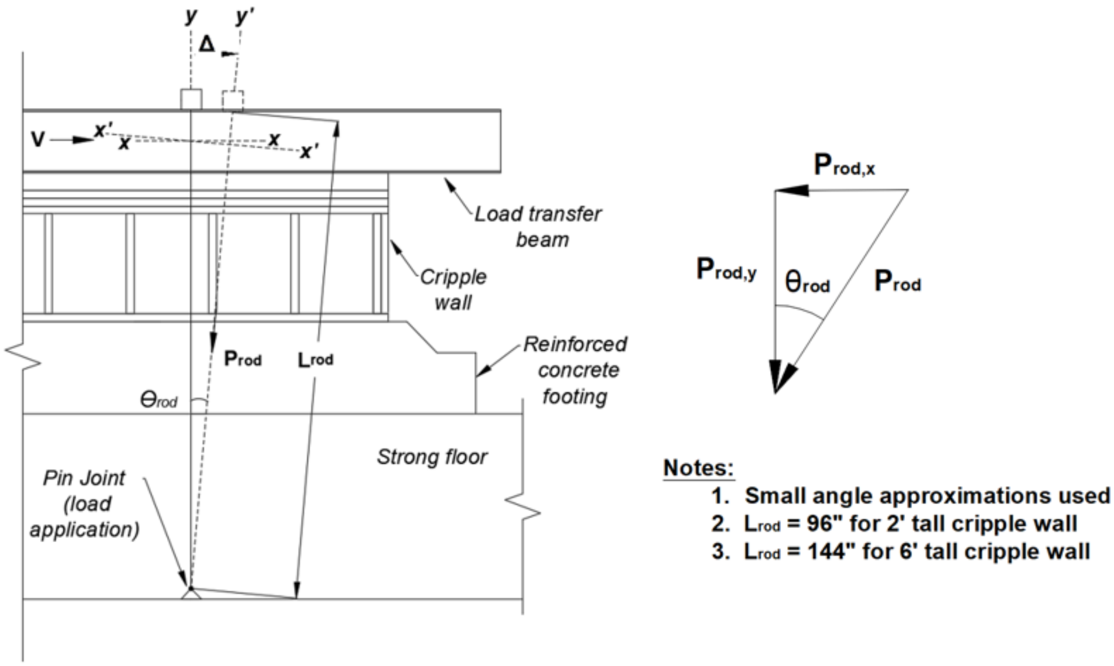


Figure 3.107 Schematic of displaced geometry for lateral load correction.

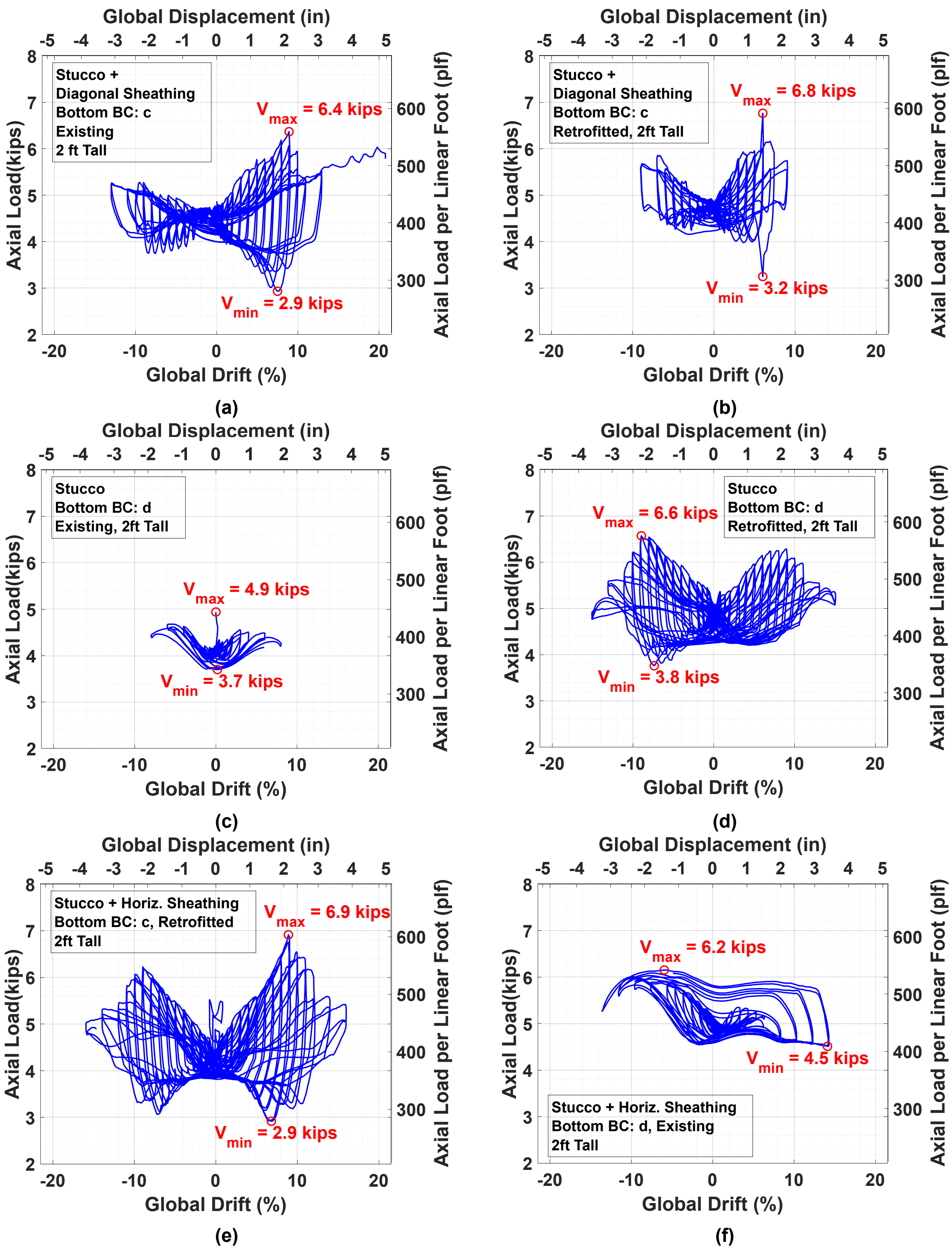


Figure 3.108 Vertical load versus global drift for specimens: (a) Specimen A-15; (b) Specimen A-16; (c) Specimen A-17; (d) Specimen A-18; (e) Specimen A-19; (f) Specimen A-20; (g) Specimen A-21; (h) Specimen A-22; (i) Specimen A-25; and (j) Specimen A-26.

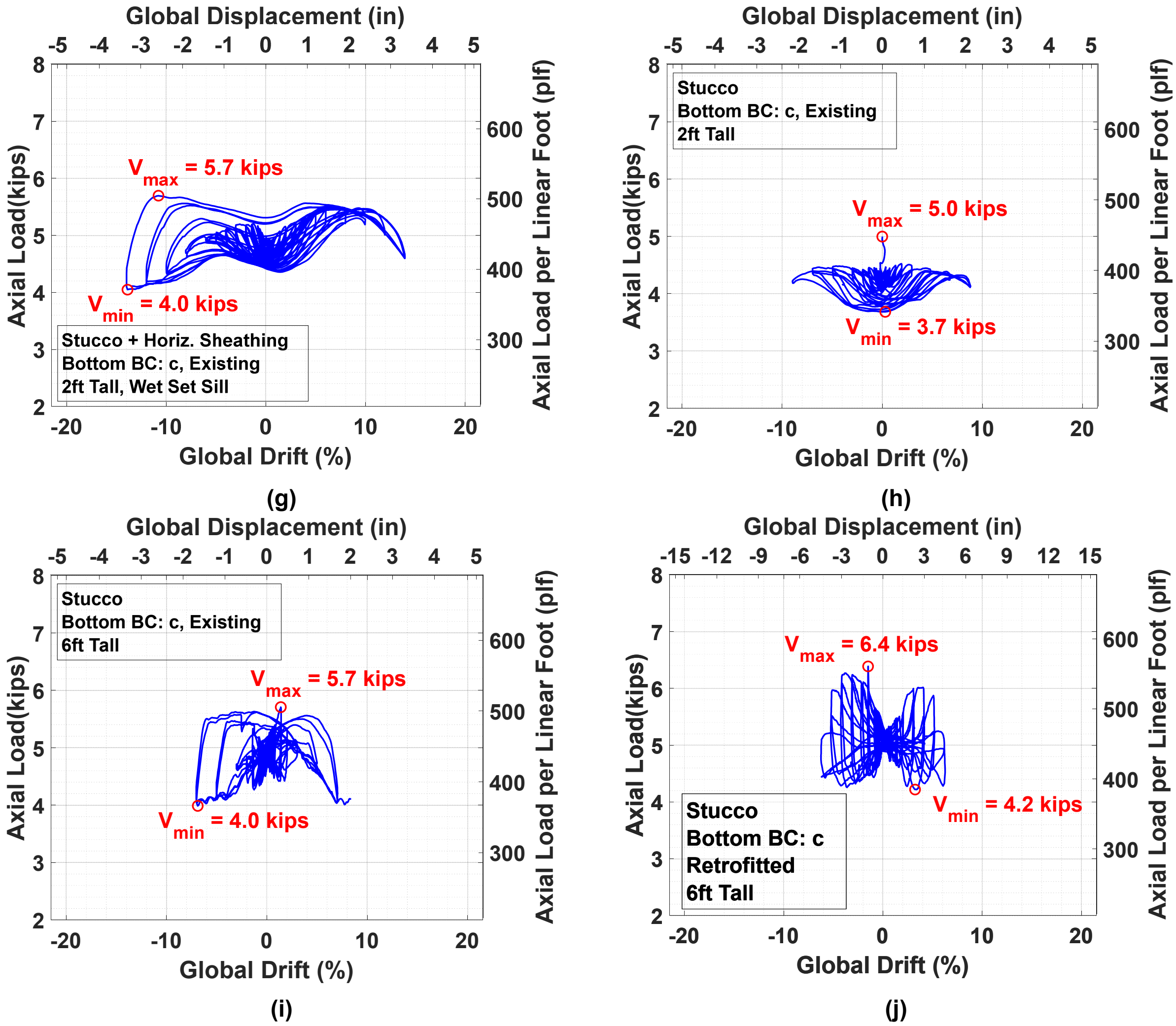


Figure 3.108 (continued).

4 Damage Characteristics

4.1 OVERVIEW

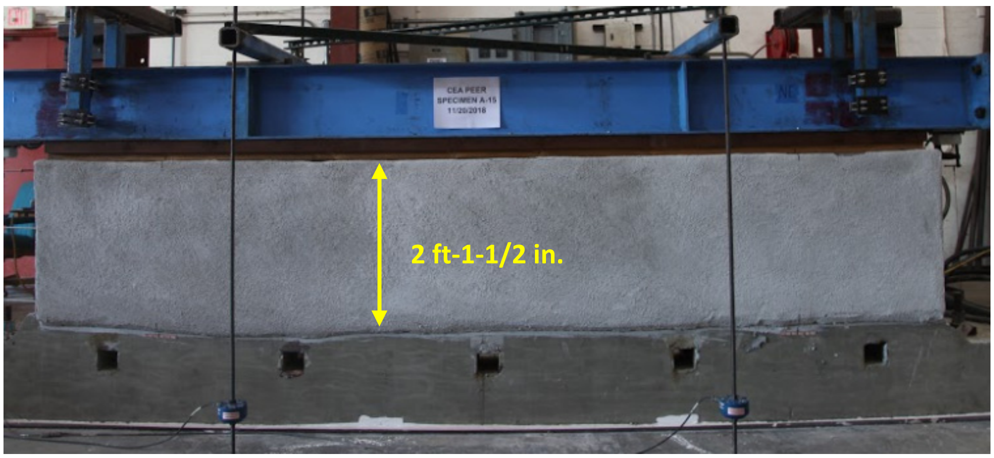
This chapter presents the physical damage characteristics as they evolved during the cyclic testing of each cripple wall specimen tested in Phase 3 and those presented from Phase 4. Tracking the physical damage of cripple walls is key to be able to make determinations about the structural integrity of a cripple wall after a seismic event. This chapter will focus on typical damage characteristics observed, including stucco cracking, nail withdrawal/rotation, plywood panel tearing, and rotation as well as uplift and splitting of framing members. Damage documentation was taken via hand notes and high-resolution photographs, as well as evaluation of video footage taken during testing. For all drift ratio levels, photographs of damage were taken at the initial push and initial pull of each drift amplitude. In addition, from the 0.2% to the 1.4% drift ratio levels, photographs were taken at the end of the cycle grouping to record the state of damage at zero imposed lateral load as well as the residual displacement that accrued in the cripple walls. The ability to relate the physical damage of a cripple wall to the lateral strength of a cripple wall is key to determining what repairs are required to fix the aesthetic and structural elements of a cripple wall and the superstructure. This chapter will be broken into sections based on the damage to each of the six cripple walls.

4.2 DAMAGE CHARACTERISTICS FROM 0.0% TO 1.4% DRIFT RATIO LEVEL (service-level range)

Understanding the physical damage characteristics of cripple walls at low-level drift amplitudes is key in determining what is a serviceable structure versus what is a structure that requires repairs before it becomes serviceable again. This section denotes service-level drift as amplitudes prior to and including 1.4% global drift ratio of the cripple wall. The damage characteristics of each of the six cripple wall specimens at these drift amplitude cycles will be described and documented. In addition, photographs of the original structure will be shown to illustrate the initial state of the structure prior to testing.

4.2.1 Specimen A-15 0.0% to 1.4% Drift Ratio Level

The photographs in Figure 4.1 show Specimen A-15 prior to testing. Specimen A-15 was an existing 2-ft-tall cripple wall with stucco over diagonal sheathing exterior finish and bottom boundary condition “c”. With this boundary condition, all finish materials are outboard of the foundation, and the stucco does not extend down the face of the foundation. The sheathing boards were composed of 1 × 6 Douglas Fir and oriented at 45° from the horizontal bottom sill. The orientation of the sheathing boards can be seen in Figure 4.1(b). Figure 4.1(e) and (f) show cracks on the stucco that occurred prior to testing. Figure 4.2 shows the cripple wall at -1.4% drift (-0.336 in.). At this point, a cross-grain crack had formed in the sill plate at the north end of the cripple wall; see Figure 4.2(c). In addition, a large piece of stucco had spalled off at the base at the location of one of the pre-existing cracks; Figure 4.2(e). Cracking and spalling of stucco occurred at both corners of the wall. Lastly, the stucco had displaced 1/4 in. from the footing at the base of the cripple wall and 1/8 in. from the framing at the top of the wall; see Figure 4.2(a) and (b).



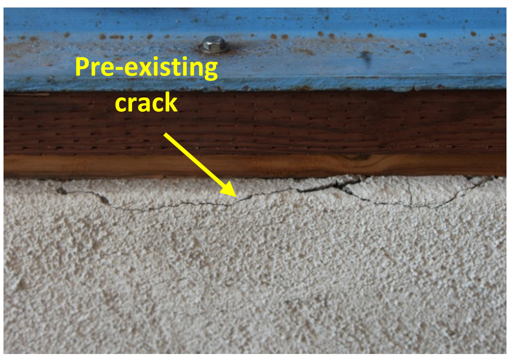
(a)

(b)

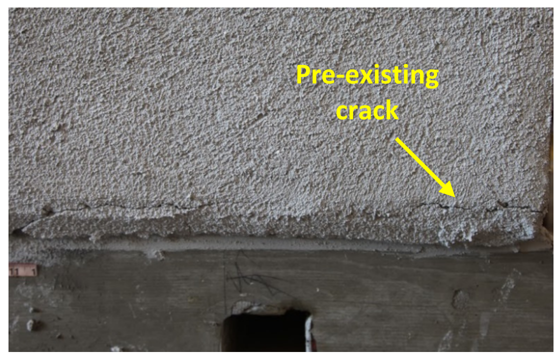
Figure 4.1 **Specimen A-15 pre-test photographs for the existing 2-ft-tall cripple wall with stucco over diagonal sheathing exterior finish and bottom boundary condition “c”: (a) exterior elevation; (b) interior elevation; (c) north-end exterior corner of wall view; (d) north-end interior corner of wall view; (e) top of north-end exterior of wall view; and (f) bottom of north-end exterior of wall view.**

(c)

(d)



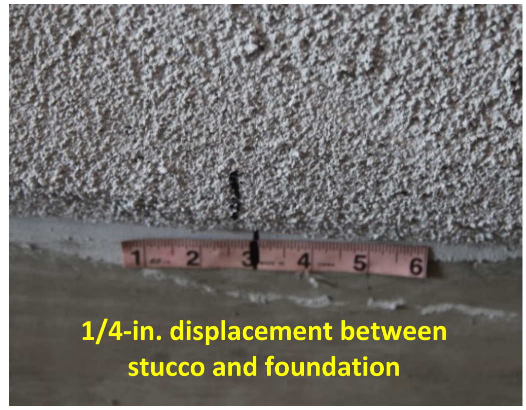
(e)



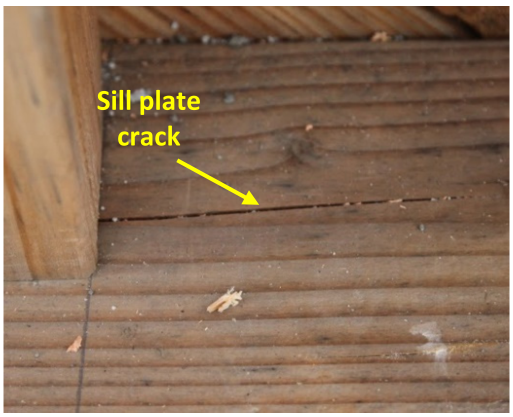
(f)

Figure 4.1 (continued).

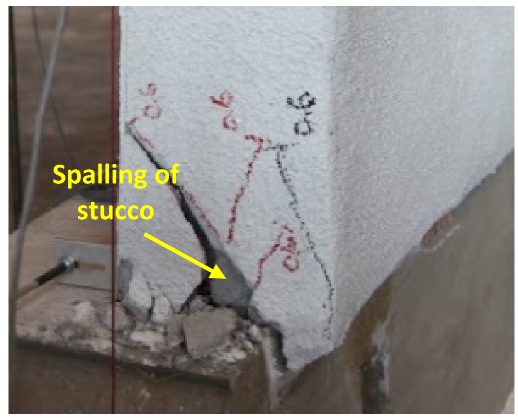
(a)



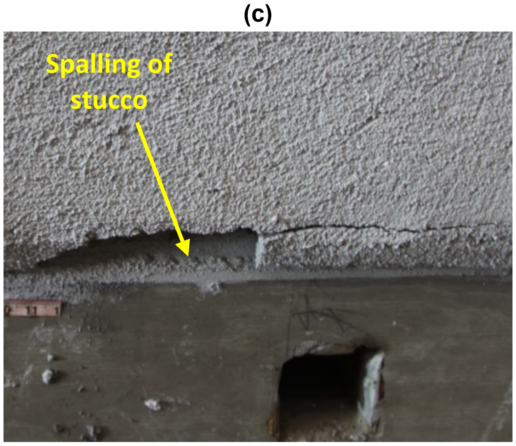
(b)



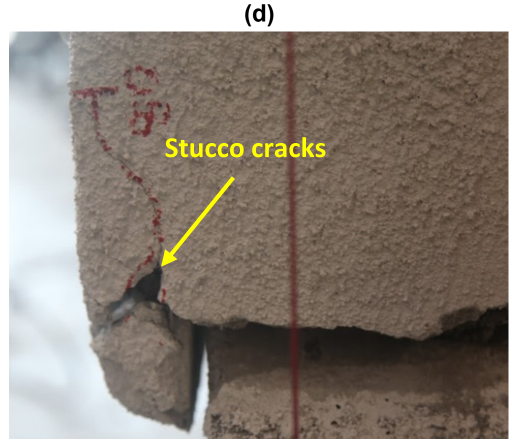
(c)



(d)



(e)



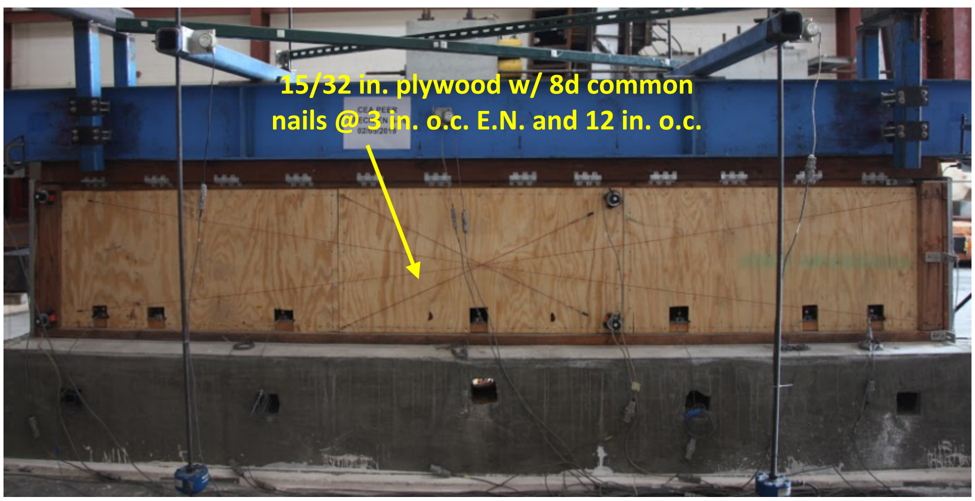
(f)

Figure 4.2 **Specimen A-15 damage state at -1.4% drift ratio @ Δ = -0.336 in.: (a) top of south-end exterior of wall view; (b) bottom of south-end exterior of wall view; (c) bottom of north-end interior of wall view; (d) bottom of south-end exterior corner of wall view; (e) bottom of north-end exterior of wall view; and (f) bottom of north-end corner of wall view.**

4.2.2 Specimen A-16 0.0% to 1.4% Drift Ratio Level

The photographs in Figure 4.3 show Specimen A-16 prior to testing. Specimen A-16 was a retrofitted 2-ft-tall cripple wall with stucco over diagonal sheathing exterior finish and bottom boundary condition “c”. It was the retrofit pair of Specimen A-15. As before with bottom boundary condition “c”, all finish materials were outboard of the foundation, and the stucco did not extend down the face of the foundation. The sheathing boards were composed of 1 × 6 Douglas Fir and oriented at 45° from the horizontal bottom sill. The 15/32-in.-thick plywood used for the retrofit was fastened with 8d common nails at 3 in. on center around the edges and 12 in. on center through the field. Four additional anchor bolts were installed during the retrofit. Five of the anchor bolts were slotted into place, and two of the anchor bolts were embedded 10 in. into the foundation and epoxied into place. There was no pre-existing damage to the wall prior to testing. Figure 4.4 shows the cripple wall at -1.4% drift (-0.336 in.). The damage to the stucco was similar to that of the unretrofitted counterpart. A vertical crack formed down the face of the specimen, as seen in Figure 4.4(d). There was no relative displacement between the finish materials and the upper top plate, with 1/4-in. displacement occurring between the stucco and the footing. On the interior, nails had begun to withdrawal at some locations [Figure 5.4(e)] and rotate at other locations; see Figure 4.4(f).

(a)



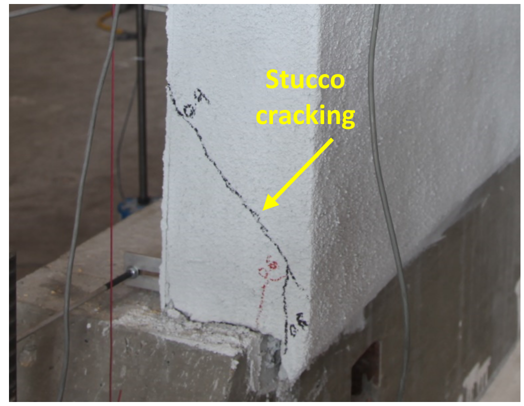
(b)

Figure 4.3 Specimen A-16 pre-test photographs for the retrofitted 2-ft-tall cripple wall with stucco over diagonal sheathing exterior finish and bottom boundary condition "c": (a) exterior elevation; (b) interior elevation; (c) north-end exterior corner of wall view; and (d) south-end interior corner of wall view.

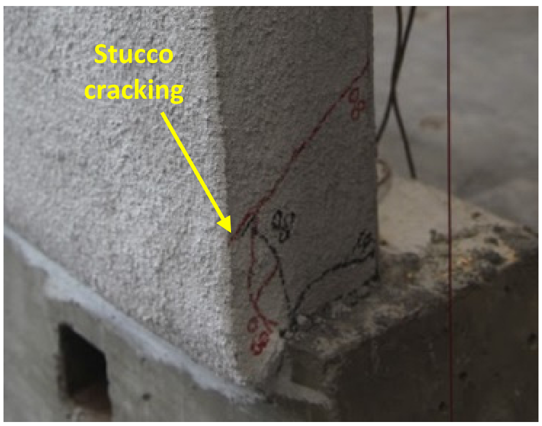
(c)

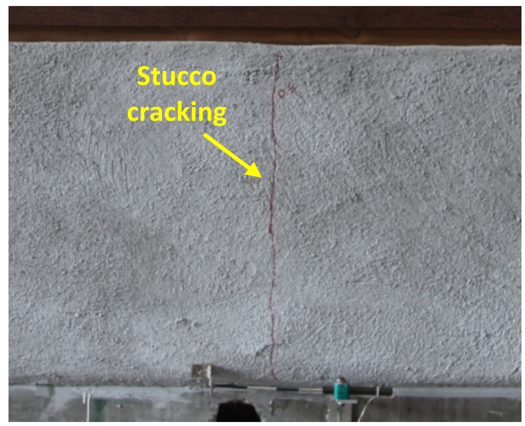
(d)

Figure 4.3 (continued).

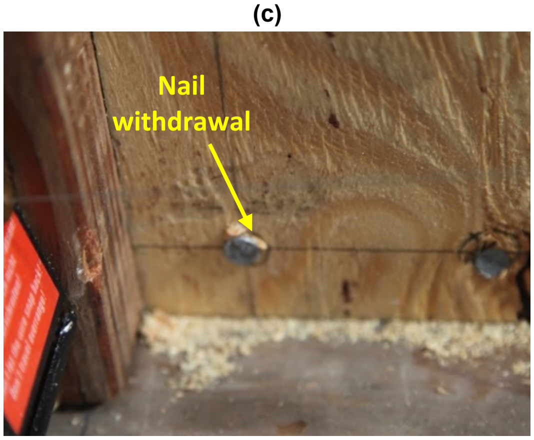


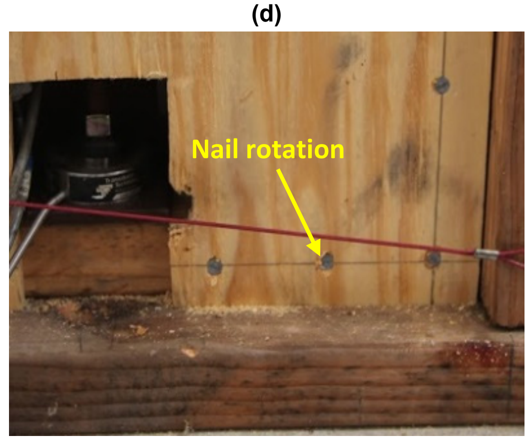
(a) (b)





(c) (d)





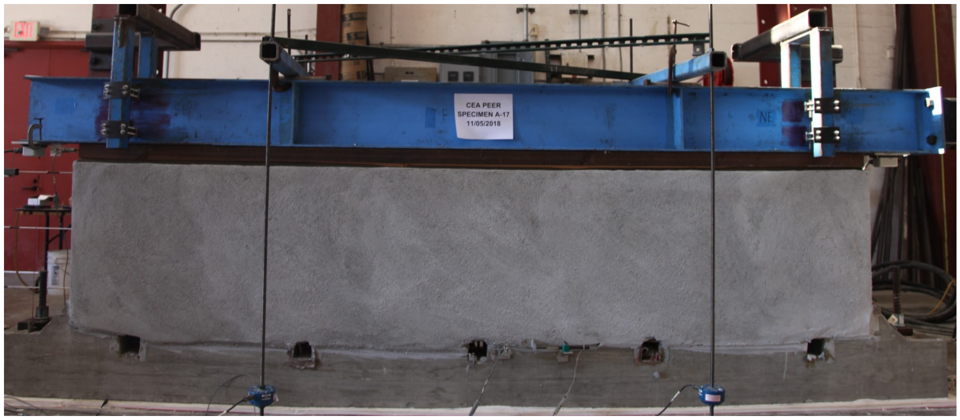
(e) (f)

Figure 4.4 **Specimen A-16 damage state at -1.4% drift ratio @ Δ =-0.336 in.: (a) top of south-end exterior of wall view; (b) bottom of south-end exterior corner of wall view; (c) bottom of north-end exterior corner of wall view; (d) middle interior of wall view; (e) bottom of north-end interior of wall view; and (f) bottom of south-end interior of wall view.**

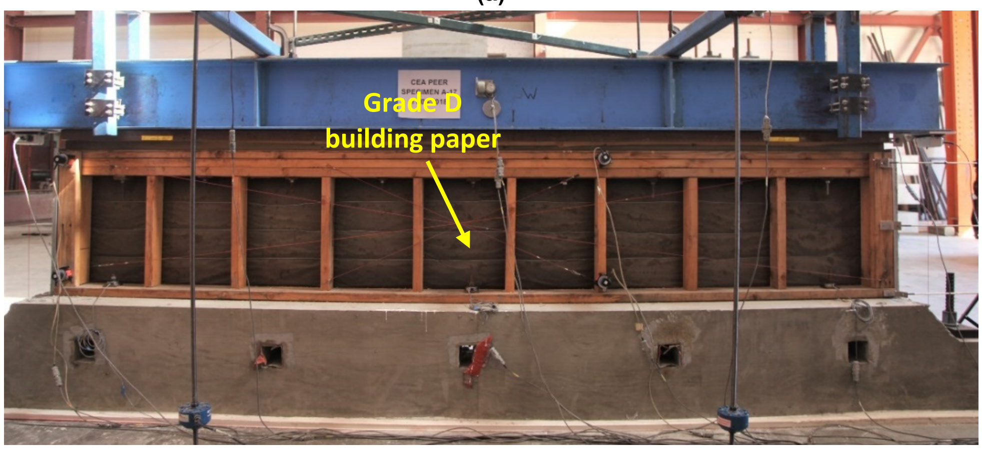
4.2.3 Specimen A-17 0.0% to 1.4% Drift Ratio Level

The photographs in Figure 4.5 show Specimen A-17 prior to testing. Specimen A-17 was an existing 2-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition “d”. With bottom boundary condition “d”, all finish materials were outboard of the foundation, and the stucco extended 8 in. down the face of the foundation. As seen in Figure 4.5(b), line wire spaced at 6 in. on center provided backing for the stucco. Grade D building paper was then placed over the line wire, and then the stucco was applied. Figure 4.3(d) shows the bottom of the south corner where the bond between the stucco and foundation had partially detached. This was the same on the north end of the specimen. The bond between the stucco and the foundation was weakened during the transportation of the specimen into the testing apparatus. Due to the nature of stucco construction (which took multiple weeks to fully install), the specimens were built on foundations and then moved into the testing apparatus. Typically, this did not damage the specimens, but those with the stucco extension at the base suffered minor damage to the bond between the stucco and the foundation when they were moved into the testing apparatus. No other damage was noted prior to testing.

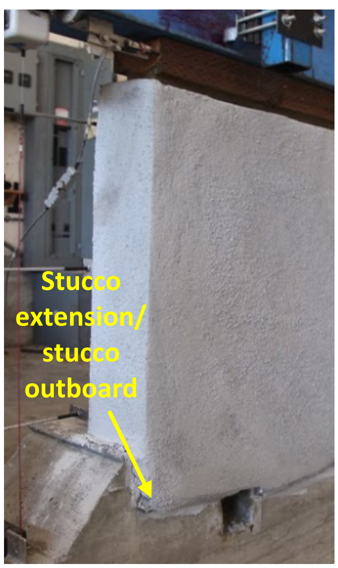
Figure 4.6 shows the state of Specimen A-17 at -1.4% drift ratio (-0.336 in.). At this point, the stucco extending down the face of the foundation had completely detached across the entire face of the cripple wall. A gap formed between the stucco extension and the foundation, as shown in Figure 4.6(e) and (f). These photographs show cracking at the corners of the specimen. Along the exterior of the cripple wall, a single vertical crack began to propagate from the top of the wall towards the base; see Figure 4.6(b). This was the largest crack that had formed, but because it formed at the +0.2% drift cycle, it is likely that this crack might have been aided by moving the cripple wall into the testing apparatus. There was no damage to the framing at this point.



(a)

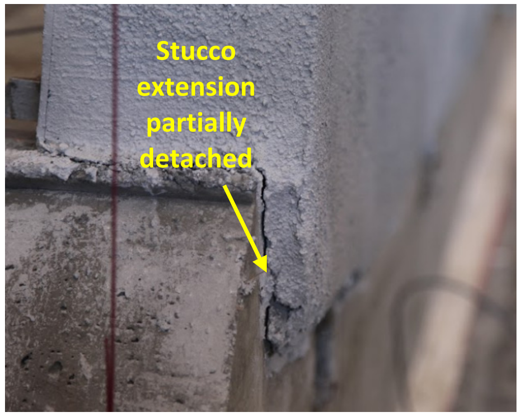


(b)



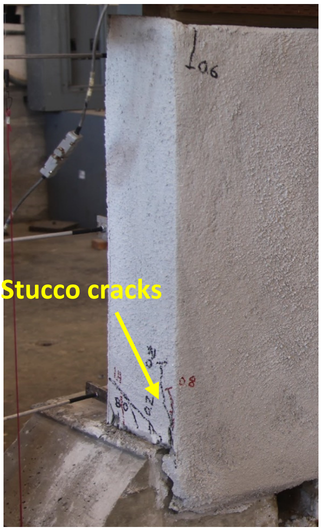
(c) (d)

Figure 4.5 **Specimen A-17 pre-test photographs for the existing 2-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition "d": (a) exterior elevation; (b) interior elevation; (c) north-end exterior corner of wall view; (d) north-end interior corner of wall view; and (e) bottom of south-end of wall corner view.**

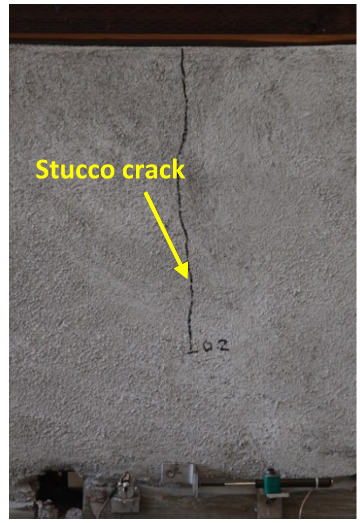


(e)

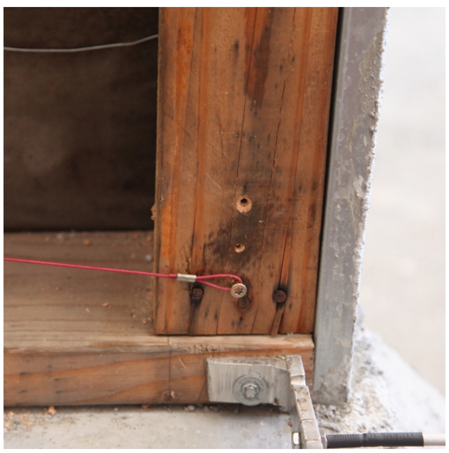
Figure 4.5 (continued).



(a)

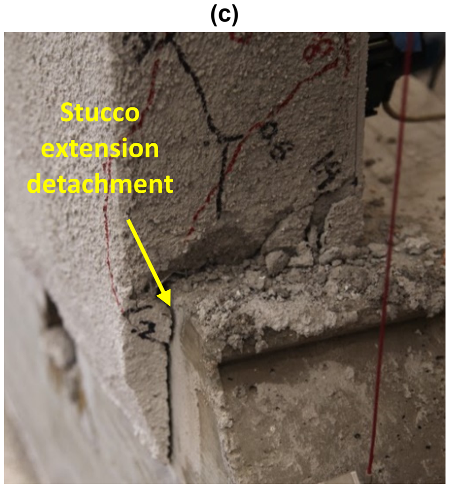


(b)

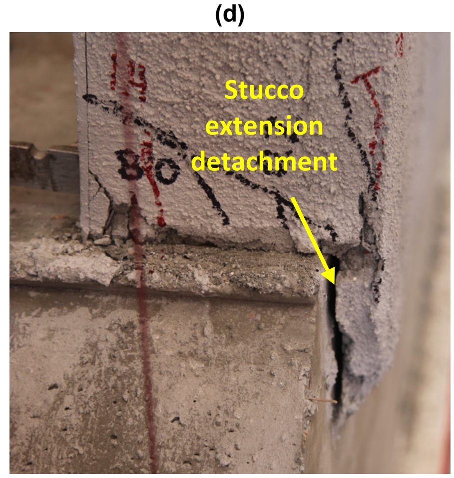


(c)

(d)



(e)



(f)

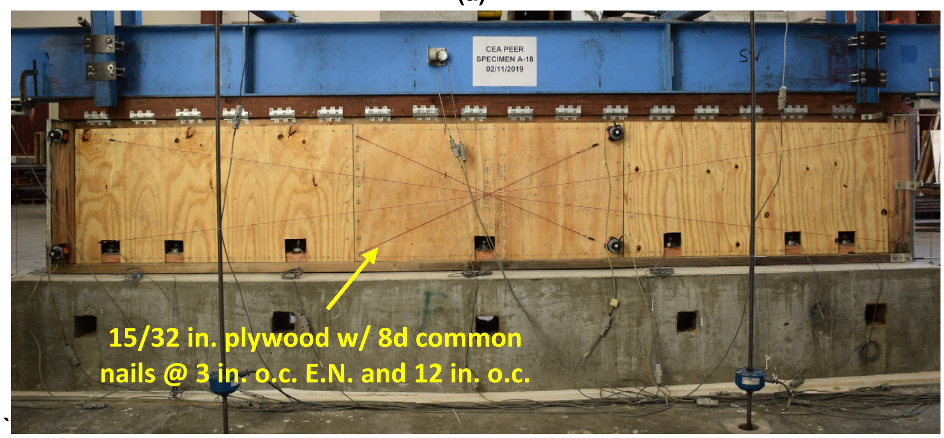
Figure 4.6 **Specimen A-17 damage state at -1.4% drift ratio @ Δ =-0.336 in.: (a) south-end exterior corner of wall view; (b) middle exterior of wall view; (c) bottom of south-end interior of wall view; (d) top of south-end interior of wall view; (e) bottom of north-end exterior corner of wall view; and (f) bottom of south-end corner of wall view.**

4.2.4 Specimen A-18 0.0% to 1.4% Drift Ratio Level

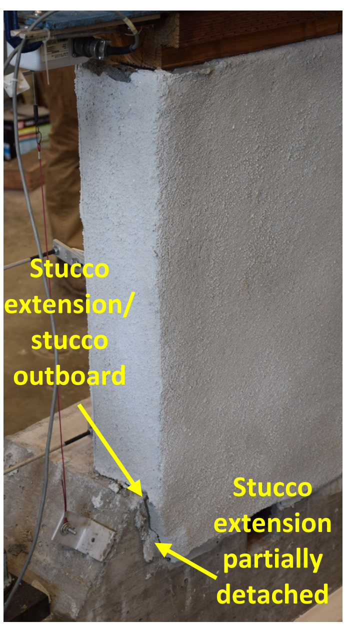
The photographs in Figure 4.7 show Specimen A-18 prior to testing. Specimen A-18 was a retrofitted 2-ft-tall wall with stucco over framing exterior finish and bottom boundary condition “d”. It was the retrofit pair of Specimen A-17. As stated before, with bottom boundary condition “d”, all finish materials were outboard of the foundation, and the stucco extended 8 in. down the face of the foundation. The 15/32-in.-thick plywood used for the retrofit was fastened with 8d common nails at 3 in. on center around the edges and 12 in. on center through the field. Four additional anchor bolts were installed during the retrofit. Five of the anchor bolts were slotted into place, and two of the anchor bolts were embedded 10 in. into the foundation and epoxied into place.

As with Specimen A-17, the stucco extension had already partially detached prior to testing; see Figure 4.7(c). Figure 5.8 shows photographs of the specimen at -1.4% drift ratio (-0.336 in.). Multiple vertical cracks had formed along the face of the cripple wall; see Figure 4.8(b). This specimen had more vertical cracks compared to any of the previous specimens. Like Specimen A-17, the stucco had fully detached from the foundation by this point, as shown in Figure 4.8(e) and (f). On the interior of the cripple wall, the plywood panels had started to rotate. As with Specimen A-16, the previous retrofitted specimen, some of the nails had begun to withdraw from the framing, and many of the nails had rotated to some degree. At this point, some of the nails had begun to pull through the plywood, as seen in Figure 4.8(d). No discernible pattern was evident as to which nails had started to withdraw from the framing and which nails had started to pull through plywood.

(a)



(b)

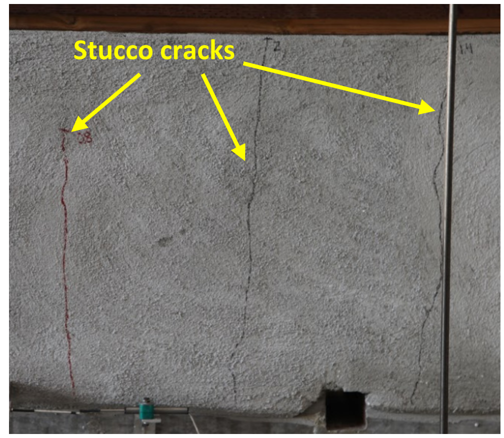


(c)

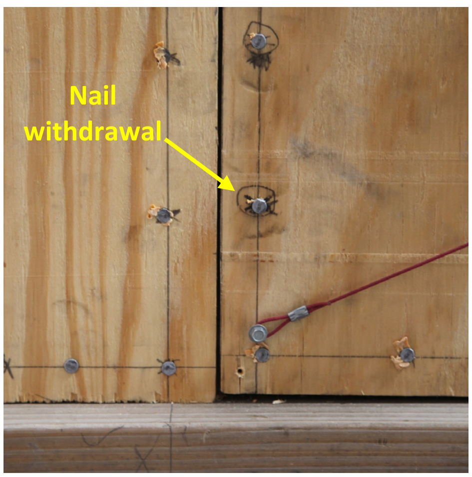
(d)

Figure 4.7 **Specimen A-18 pre-test photographs for the retrofitted 2-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition "d": (a) exterior elevation; (b) interior elevation; (c) south-end exterior corner of wall view; and (d) south-end interior corner of wall view.**

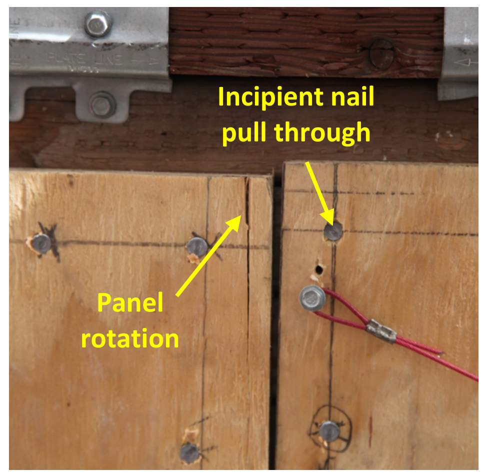
(a)



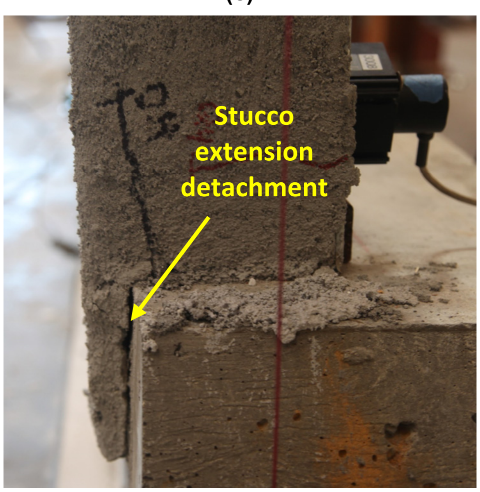
(b)



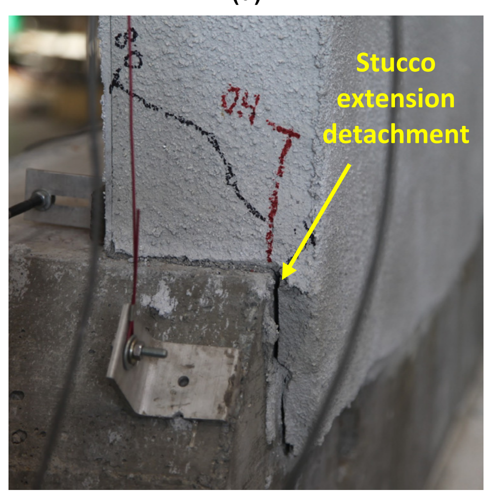
(c)



(d)



(e)



(f)

Figure 4.8 **Specimen A-18 damage state at -1.4% drift ratio @ Δ = -0.336 in.: (a) top of south-end exterior of wall view; (b) middle exterior of wall view; (c) bottom interior of wall view (north and middle panels); (d) top interior of wall view (north and middle panels); (e) bottom of north-end corner of wall view; and (f) bottom of south-end corner of wall view.**

4.2.5 Specimen A-19 0.0% to 1.4% Drift Ratio Level

The photographs in Figure 4.9 show Specimen A-19 prior to testing. Specimen A-19 was a retrofitted 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish and bottom boundary condition “c”. There was no exact retrofit pair for Specimen A-19. The sheathing boards were 1 × 6 Douglas Fir. The 15/32 in.-thick plywood used for the retrofit was fastened with 8d common nails at 3 in. on center around the edges and 12 in. on center through the field. Four additional anchor bolts were installed during the retrofit. Five of the anchor bolts were slotted into place, and two of the anchor bolts were embedded 10 in. into the foundation and epoxied into place. A piece of stucco at the base of the north end of the specimen had detached prior to testing; see Figure 5.9(e). Besides the detached pieced of stucco, no other noticeable damage to the cripple wall prior to testing was detected.

Figure 4.10 shows the cripple wall at -1.4% drift ratio (-0.336 in.). At the top of the cripple wall, the sheathing had displaced by 1/8 in. relative to the framing [Figure 4.10(a)], and both finish materials had displaced by 1/4 in. relative to the foundation; see Figure 4.10(b). At the bottom of both corners, cracks had formed in the stucco; see Figure 4.10(c) and (f). With all stucco specimens tested, there was increased cracking concentrated at the bottom of the corners due to the corners bearing on the foundation. Along the face of the specimen, a diagonal and a vertical crack had formed, as shown in Figure 4.10(e). On the interior, damage to the plywood was the same experienced by the previous retrofitted specimens. There were small rotations of the panels, withdrawal of the nails at some locations, and rotation of many of the edge nails. The beginning of nail withdrawal at the base of the panels can be seen in Figure 4.10(d).

(a)

(b)

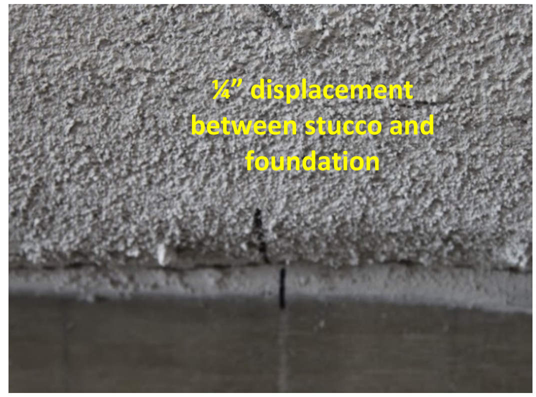
Figure 4.9 **Specimen A-19 pre-test photographs for the retrofitted 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish and bottom boundary condition "c": (a) exterior elevation; (b) interior elevation; (c) south-end interior corner of wall view; (d) south-end exterior corner of wall view; and (e) bottom of north-end exterior of wall view.**

(c)

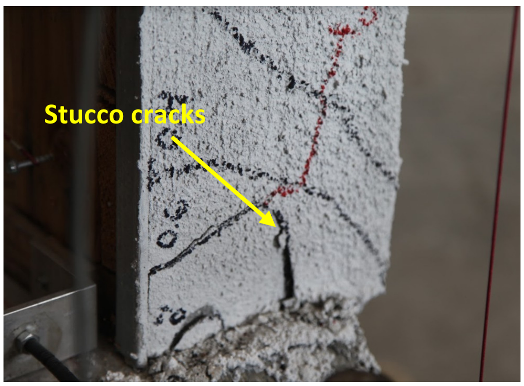
(d)

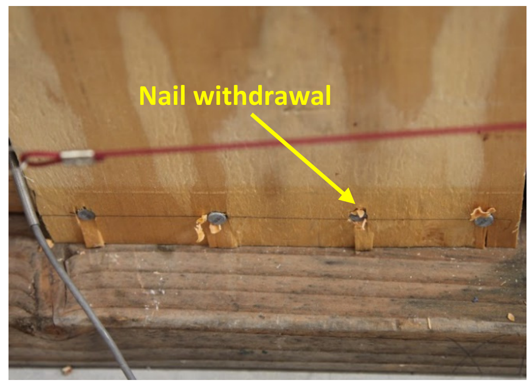
(e)

Figure 4.9 (continued).

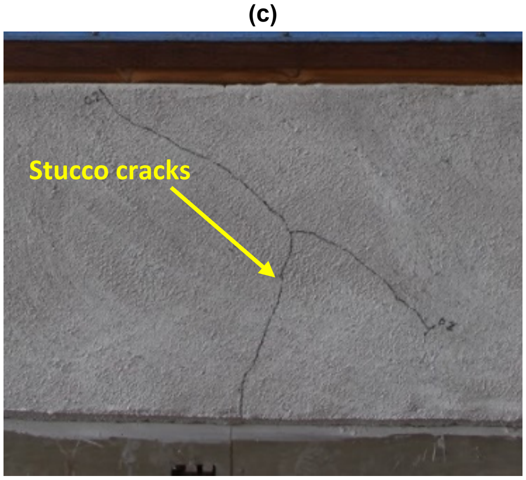


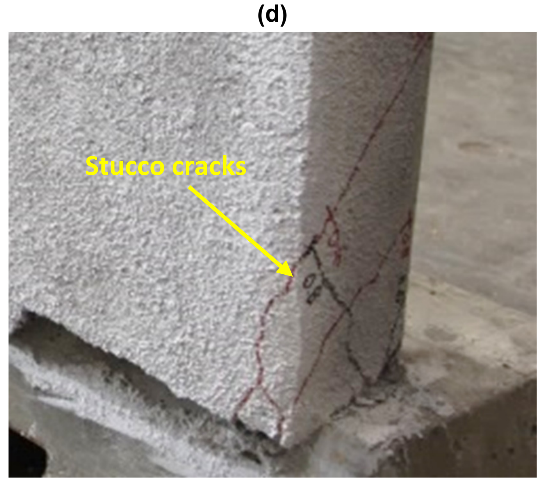
(a) (b)





(c) (d)





(e) (f)

Figure 4.10 **Specimen A-19 damage state at -1.4% drift ratio @ Δ = -0.336 in.: (a) top of south-end exterior of wall view; (b) bottom of south-end exterior of wall view; (c) bottom of south-end interior corner of wall view; (d) bottom interior of wall view (south panel); (e) middle exterior of wall view; and (f) bottom of north-end exterior corner of wall view.**

4.2.6 Specimen A-20 0.0% to 1.4% Drift Ratio Level

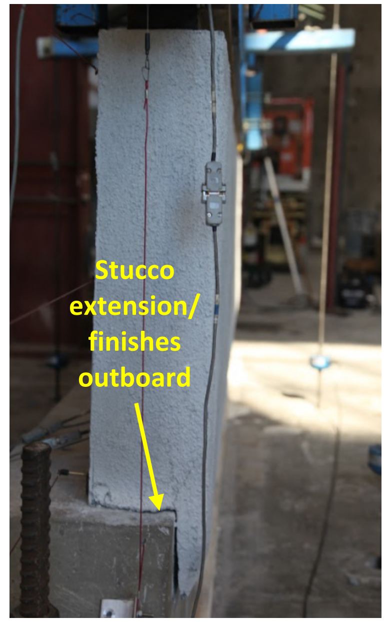
The photographs in Figure 4.11 show Specimen A-21 prior to testing. Specimen A-21 was an existing 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish and bottom boundary condition “d”. The horizontal sheathing boards were 1 × 6 Douglas Fir. Full boards were installed top and bottom and then the middle board was cut-to-fit; see Figure 4.11(b). The stucco extension had partially detached from the framing prior to testing; see Figure 4.11(d). Along the face of the specimen, a vertical crack had propagated from the base of the wall to around to nearly the top which can be seen in Figure 4.11(e). No other pre-existing damage was noted. In Figure 4.12, the state of the cripple wall is shown at -1.4% drift ratio (-0.336 in.). There was a 1/8-in. displacement between the finish materials and the framing [Figure 4.12(a)] and a ¼ in. displacement between the finish materials and the foundation; see Figure 4.12(b). These displacements are consistent with that experienced by Specimen A-15, the existing cripple wall with the stucco over diagonal sheathing finish. Small cracks formed at various locations along the bottom of the face of the cripple wall; see Figure 4.12(c) and (d). At this point, the stucco extension had fully detached from the footing, which is shown in Figure 4.12(e) and (f). The same cracking pattern at the bottom of the corners occurred as with all of the previous specimens.

(a)

(b)

Figure 4.11 **Specimen A-20 pre-test photographs for the existing 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish and bottom boundary condition "d": (a) exterior elevation; (b) interior elevation; (c) south-end interior corner of wall view; (d) south-end corner of wall view; and (e) middle exterior of wall view.**

(c)



(d)

(e)

Figure 4.11 (continued).

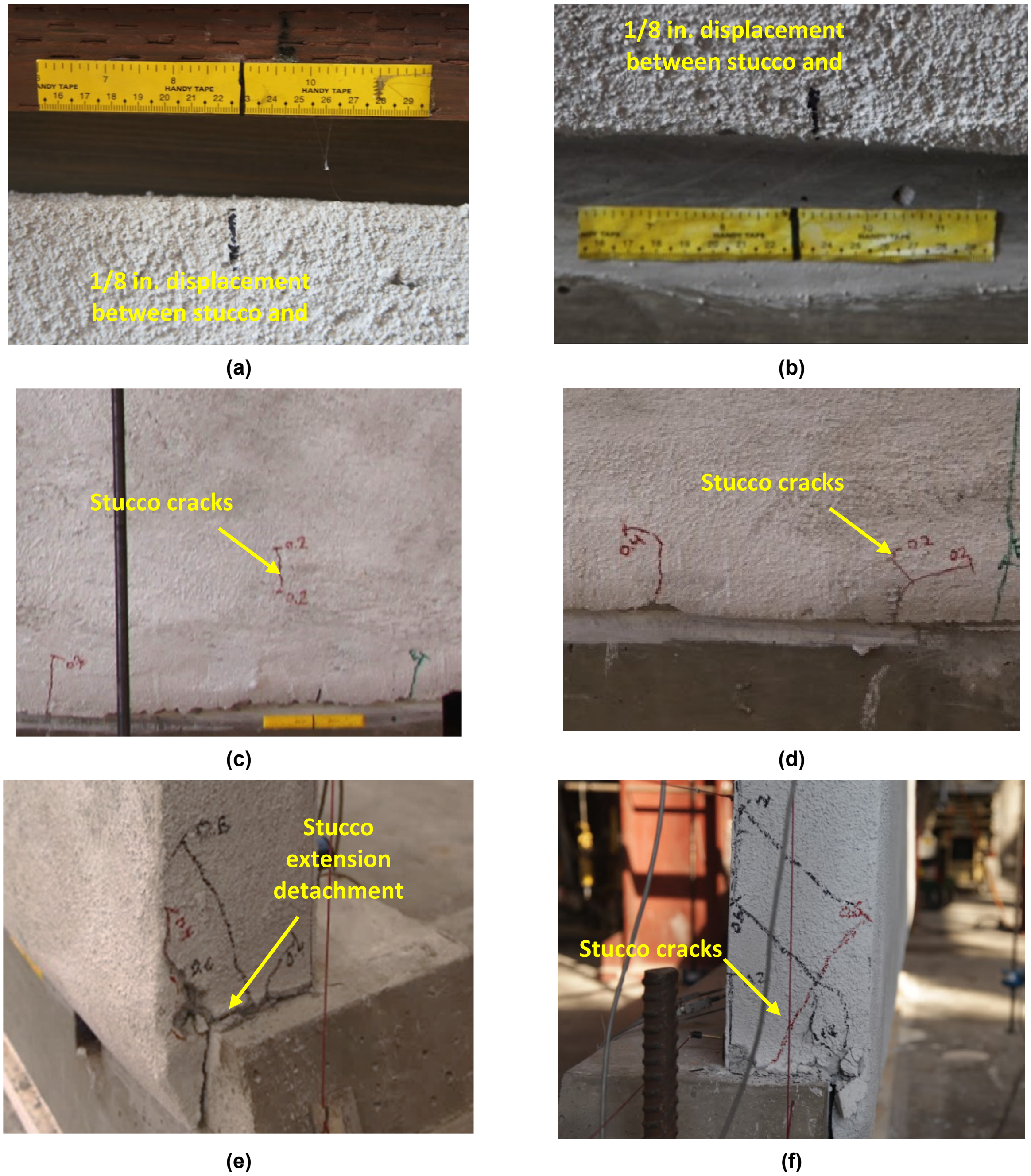


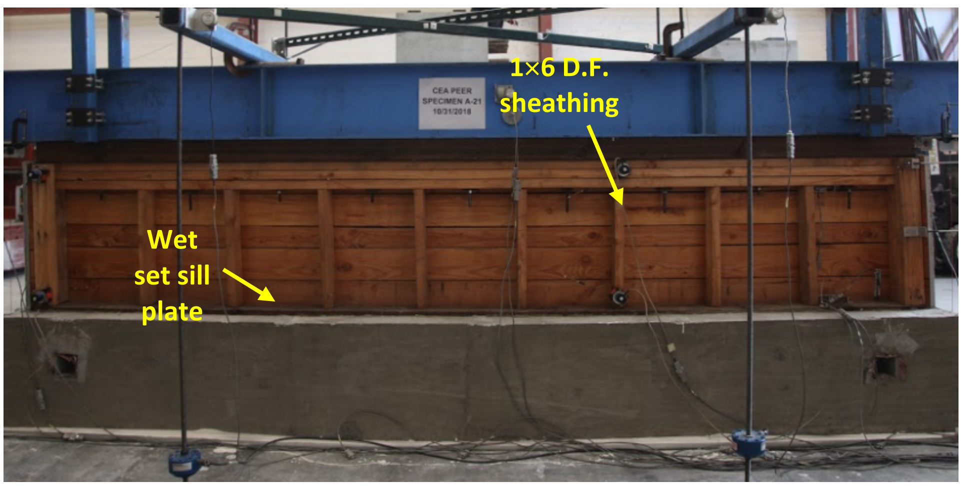
Figure 4.12 Specimen A-20 damage state at -1.4% drift ratio @ Δ = -0.336 in.: (a) top of south-end exterior of wall view; (b) bottom of south-end exterior of wall view; (c) bottom of middle exterior of wall view; (d) bottom of north-end exterior of wall view; (e) bottom of north-end exterior corner of wall view; and (f) bottom of south-end corner of wall view.

4.2.7 Specimen A-21 0.0% to 1.4% Drift Ratio Level

The photographs in Figure 4.13 show Specimen A-21 prior to testing. Specimen A-21 was an existing 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish and bottom boundary condition “c”. Instead of a typical sill plate that is fastened to the foundation with anchor bolts, Specimen A-21 was constructed with a wet set sill plate. Recall that a wet set sill plate is a sill plate that is placed into the foundation when the concrete is poured so that the foundation cures around the sill plate. In order to provide uplift resistance to the sill plate, two 30d common nails were fastened at 24 in. on center along the span of the sill plate and embedded with the sill plate into the wet concrete. The sill plate was embedded 1 in. into the foundation; see Figure 4.13(c). The wet set sill plate was a nominal 2 × 6, construction-grade redwood member that was different from the #2 Douglas Fir sill plates used in all other cripple walls. Because the sill plate was already embedded before the framing was constructed, the studs were fastened to the sill plate with three 8d nails, tow-nailed into place, instead of the typical two 16d nails.

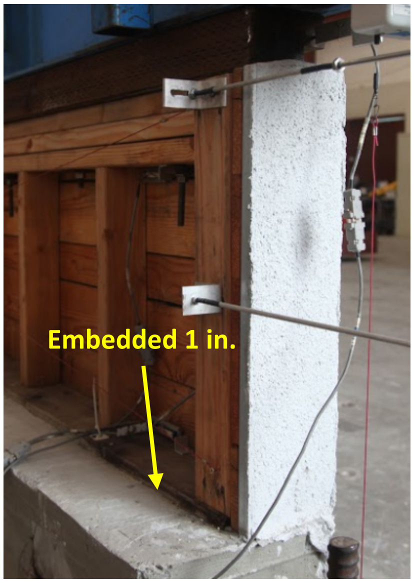
A possible deficiency of the wet set sill plate was that there was only 1/2 in. of sill plate available to attach sheathing and stucco fasteners. This was a large reduction in edge distance compared to other specimens whereby the sill plate rested on the foundation (1/2 in. versus 1-1/2 in. of available area to connect fasteners). There was no pre-existing damage to the specimen prior to testing. Figure 4.14 shows the cripple wall at -1.4% drift ratio (-0.336 in.). Multiple vertical cracks had begun to propagate from the top of the cripple wall to the base; see Figure 4.14(a). More severe cracking occurred at the top and bottom of the corners compared to previous specimens; see Figure 4.14(b), (e), and (f). This is likely due to there being no displacement between the sill plate and the foundation due to the wet set sill plate not moving; therefore, all the imposed displacement was carried by the cripple wall. On the interior, there was slight rotation of the studs as well as slight withdrawal of the toe-nails from the studs; see Figure 4.14(c) and (d).

(a)



(b)

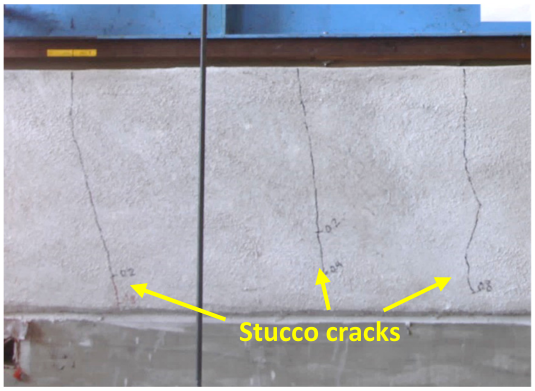
Figure 4.13 Specimen A-21 pre-test photographs for the existing 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish, bottom boundary condition "c", and wet set sill plate: (a) exterior elevation; (b) interior elevation; (c) south-end interior corner of wall view; and (d) south-end exterior corner of wall view.



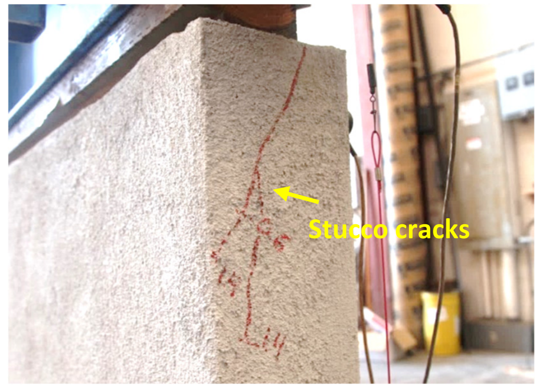
(c)

(d)

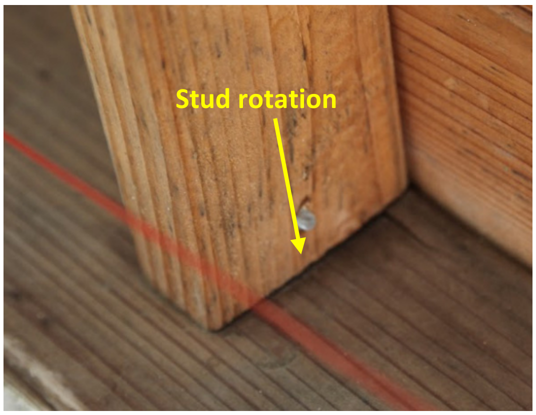
Figure 4.13 (continued).



(a)

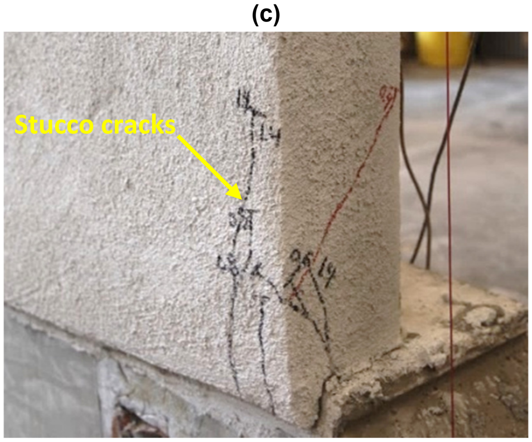


(b)

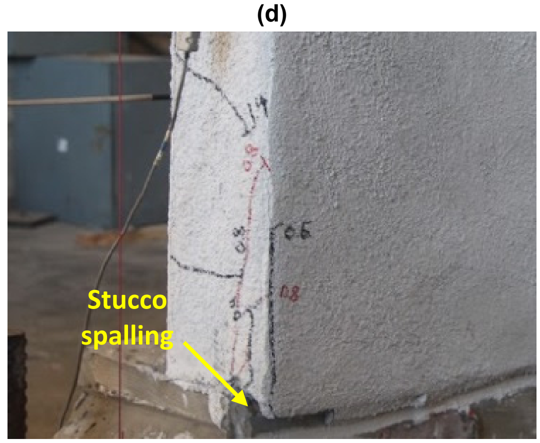


(c)

(d)



(e)



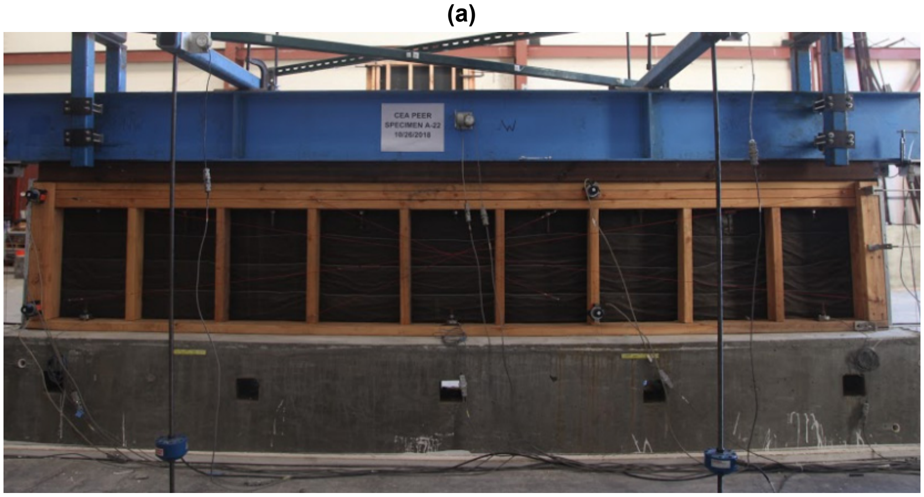
(f)

Figure 4.14 Specimen A-21 damage state at -1.4% drift ratio @ Δ = -0.336 in.: (a) middle exterior of wall view; (b) top of north-end exterior corner of wall view; (c) bottom of middle interior of wall view; (d) bottom of middle interior of wall view; (e) bottom of north-end exterior corner of wall view; and (f) bottom of south-end exterior corner of wall view.

4.2.8 Specimen A-22 0.0% to 1.4% Drift Ratio Level

The photographs in Figure 4.15 show Specimen A-22 prior to testing. Specimen A-22 was an existing 2-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition “c”. With the exception of the stucco extension, this specimen was identical to Specimen A-17. Although the bond between the stucco and the foundation had lost much of its attachment, it was expected that the two cripple walls would behave similarly. There was no pre-existing damage to the cripple wall prior to testing. Figure 4.16 shows the cripple wall at -1.4% drift ratio (-0.336 in.). At the top of the specimen, there was a 1/8 in. displacement between the stucco and the framing [Figure 4.16(a)], and at the bottom, there was a 1-4-in. displacement between the stucco and the foundation; see Figure 4.1(b). These were the same amount of displacements exhibited by Specimen A-17. At the corners, stucco had begun to spall off at the base due to the crushing of the stucco on the footing that would occur; see Figure 4.16(c). Small cracks were concentrated at the corners but were not seen elsewhere at this point; see Figure 4.16(c) and (d). This was again due to the bearing of the stucco on the foundation at the corners. On the interior, small rotations of the stud had begun to be visible [Figure 4.16(e)] and a crack formed at the bottom of the inner end stud on the south end of the cripple wall; see Figure 4.16(f).

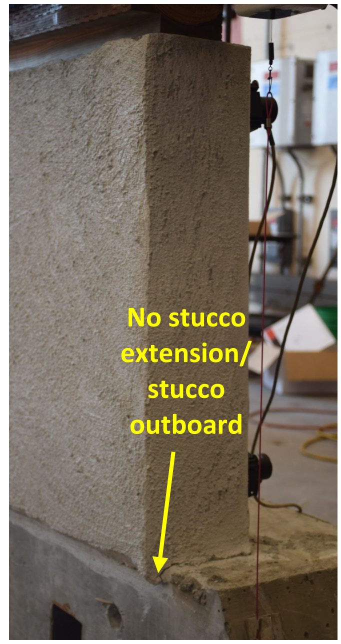
(a)



(b)

Figure 4.15 Specimen A-22 pre-test photographs for the existing 2-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition “c”: (a) exterior elevation; (b) interior elevation; (c) south-end interior corner of wall view; and (d) north-end exterior corner of wall view.

(c)



(d)

Figure 4.15 (continued).

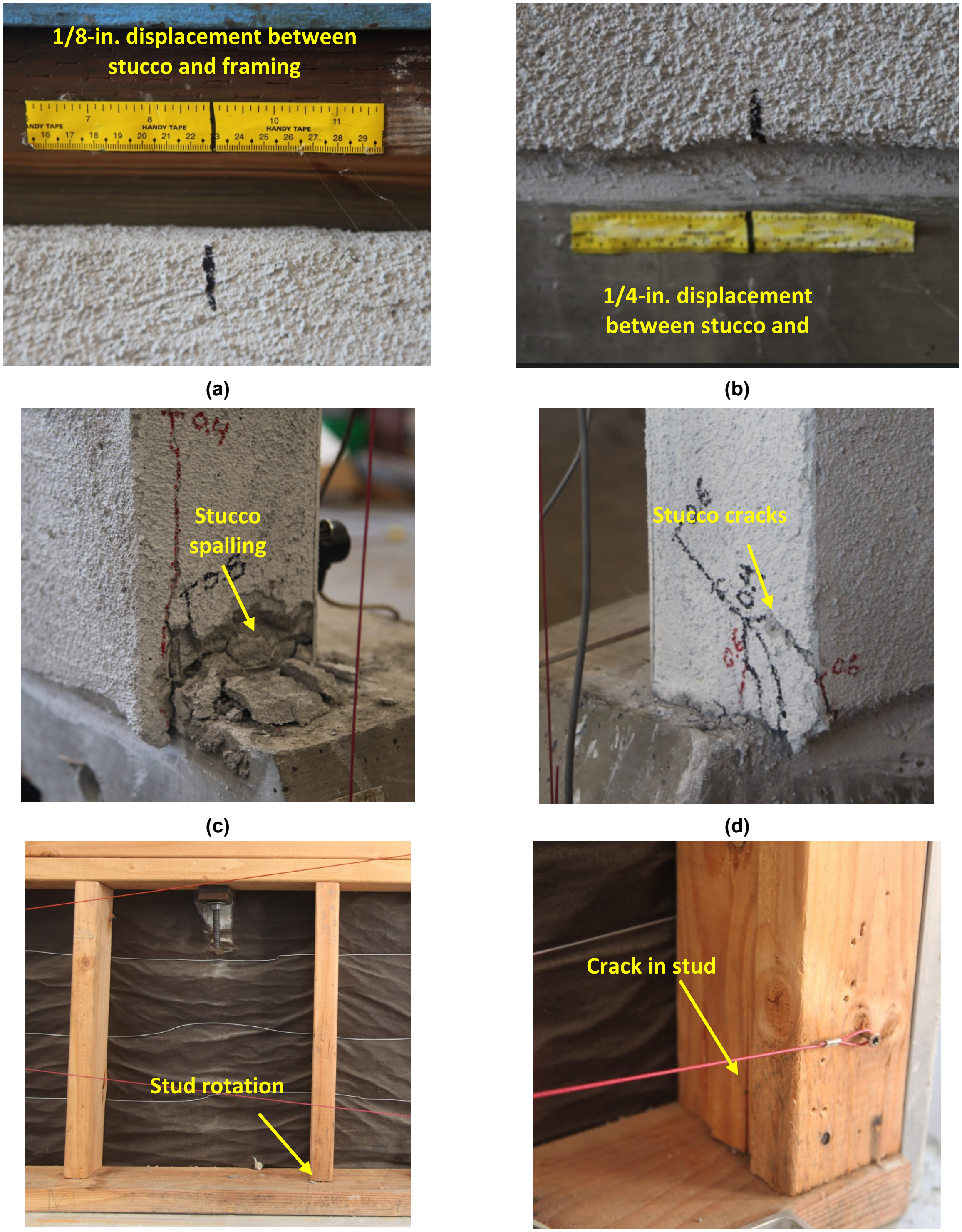
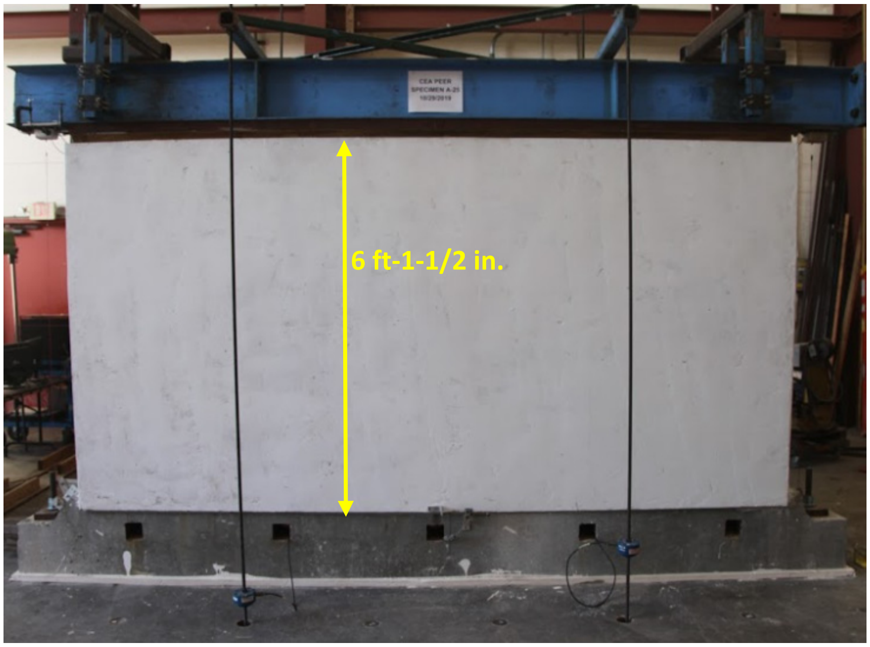


Figure 4.16 Specimen A-22 damage state at -1.4% drift ratio @ Δ = -0.336 in.: (a) south-end exterior of wall view; (b) bottom of south-end exterior of wall view; (c) bottom of north-end exterior corner of wall view; (d) bottom of south-end exterior corner of wall view; (e) middle interior of wall view; and (f) bottom of south-end interior corner of wall view.

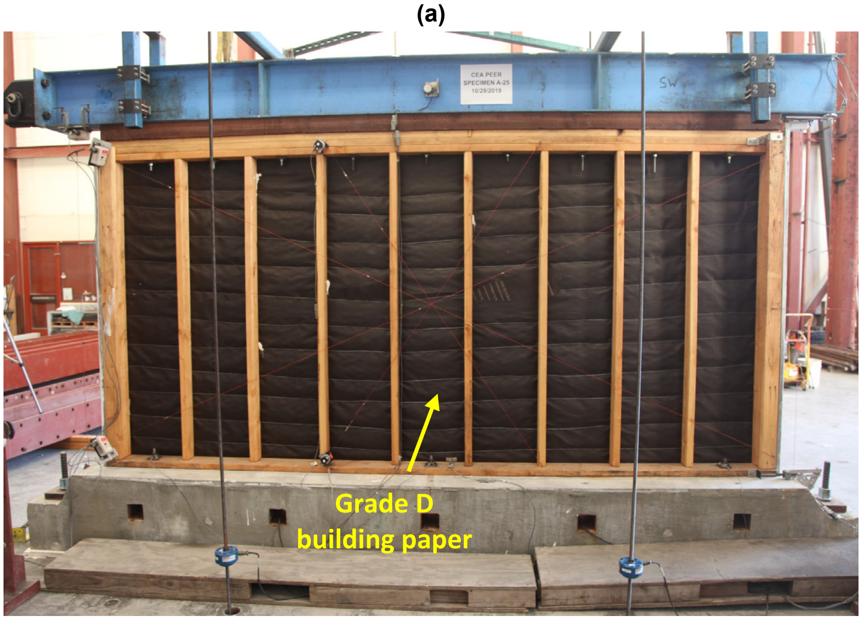
4.2.9 Specimen A-25 0.0% to 1.4% Drift Ratio Level

The photographs in Figure 4.17 show Specimen A-25 prior to testing. Specimen A-25 was an existing 6-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition “c”. Specimen A-25 was identical to Specimen A-21 with the exception of height, i.e., 2 ft tall versus 6 ft tall. This was the first wet finished 6-ft-tall specimen tested in this program. As shown in Figure 4.17(d), the stucco appears to have some extension down the face of the footing, but because there was no attachment of the stucco to the footing, this small extension had no effect of the performance of the cripple wall. There was no pre-existing damage to the specimen prior to testing.

Figure 4.18 shows the cripple wall at -1.4% drift ratio (-1.008 in.). It should be noted that at -1.4% drift, lateral strength was achieved. This was the earliest strength was achieved by any of the cripple walls tested in the entire program. An exterior elevation is provided in Figure 4.18(a) to show the propagation of diagonal cracks along the face of the stucco. The direction of the diagonal cracks was based on the direction of loading. When the cripple wall was pushed on (displaced in the south direction), cracks propagated from bottom south to top north; when the cripple wall was pulled on (displaced in the north direction), cracks propagated from bottom north to top south. Vertical cracks also propagated from the base of the wall to the top of the wall at both ends; see Figure 4.18(b) and (c). These cracks indicated that the stucco had begun detaching from the furring nails, starting at the sill plate and then working up the studs. Once the stucco began to detach from the furring nails, it was no longer able to provide resistance at the points of detachment, eventually resulted in a loss of capacity for the specimen. The same trend was exhibited for all stucco finished specimens and explains why the crack openings were larger at the base of the specimen (stucco moving out laterally from the sill plate). There was a large concentration of cracks at both corners. At the base of the corners, the cracks tend to be vertical and attributed to the bearing of the stucco on the foundation, but further up the height of the wall, the cracks were diagonal, which were due to the lateral displacement of the stucco finish. The diagonal cracks began to appear further up the wall at larger displacement amplitudes. Both corners experienced spalling of the stucco at the bottom due to the bearing of the finish on the foundation; see Figure 4.18(d) and (e). On the interior, the framing members experienced as much as 1/4-in. displacement through the middle of the cripple wall, as seen in Figure 4.18(f). The studs also exhibited rotation and uplift at the ends; see Figure 4.18(g).



(a)



(b)

Figure 4.17 **Specimen A-25 pre-test photographs for the existing 6-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition "c": (a) exterior elevation; (b) interior elevation; (c) north-end interior corner of wall view; and (d) south-end exterior corner of wall view.**

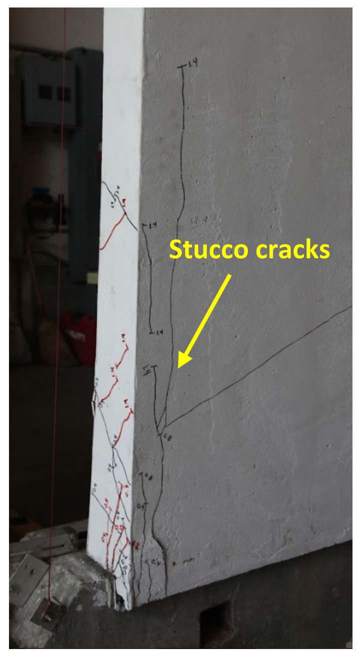
(c)

(d)

Figure 4.17 (continued).

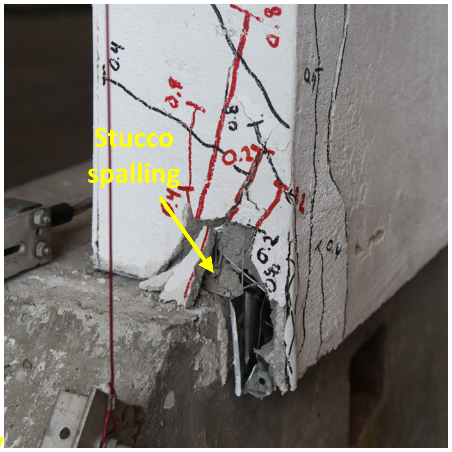
(a)

(b)

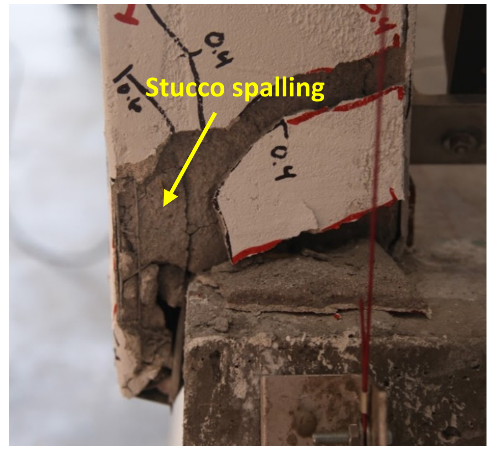


(c)

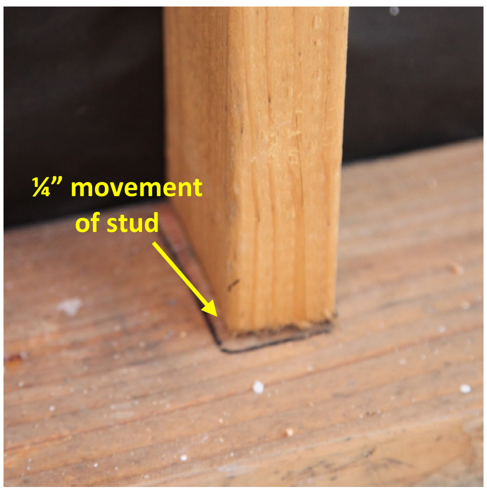
Figure 4.18 Specimen A-25 damage state at -1.4% drift ratio @ Δ = -1.008 in.: (a) exterior elevation; (b) north-end exterior corner of wall view; (c) south-end exterior corner of wall view; (d) bottom of south-end exterior corner of wall view; (e) bottom of north-end corner of wall view; (f) bottom of middle interior of wall view; and (g) bottom of south-end interior corner of wall view.



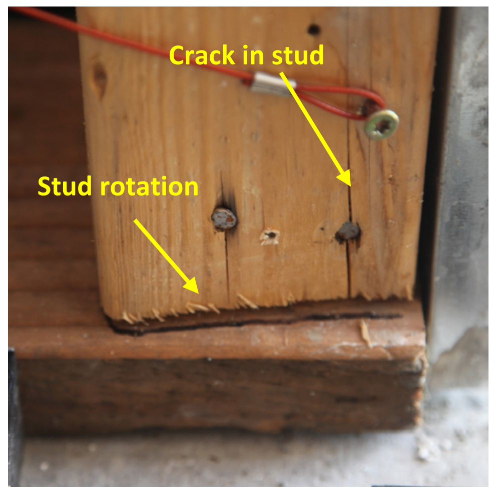
(d)



(e)



(f)



(g)

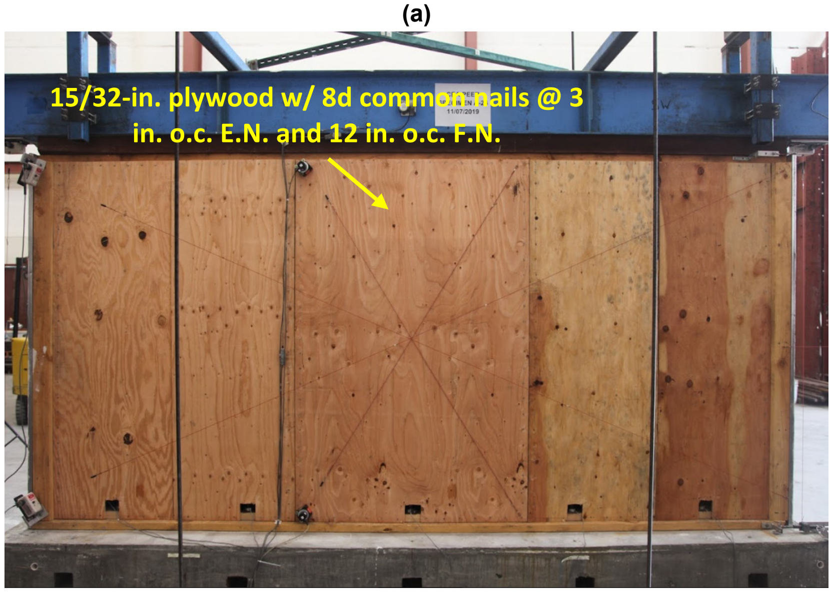
Figure 4.18 (continued).

4.2.10 Specimen A-26 0.0% to 1.4% Drift Ratio Level

The photographs in Figure 4.19 show Specimen A-26 prior to testing. Specimen A-26 was a retrofitted 6-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition “c”. Specimen A-26 was the retrofit pair to Specimen A-25. Specimen A-26 was retrofitted with 15/32-in. thick plywood panels, fastened with 8d common nails at 3 in. on center around the edges and 12 in. on center through the field; see Figure 4.19(b). Four additional anchor bolts were installed during the retrofit. Three of the anchor bolts were slotted into place, and four of the anchor bolts were embedded 10 in. into the foundation and epoxied into place. The outermost anchor bolts were connected to tie-downs, which were used to provide uplift resistance to the cripple wall. There was no evidence of pre-existing damage to the wall prior to testing.

Figure 4.20 shows the state of the cripple wall at -1.4% drift ratio (-1.008 in.). 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 4.20(a) and (b). The unretrofitted specimen exhibited the diagonal cracking pattern at the corners. In Figure 4.20(b), a vertical crack began 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 as shown by the gap forming between the face of the foundation and the stucco; see Figure 4.20(a). On the interior, the panels had begun to rotate; see Figure 4.20(c)–(e). The fasteners had rotated in many locations, especially at the base of the cripple wall; see Figure 4.20(d). At the top of the cripple wall, fasteners tended to withdraw from the framing; see Figure 4.20(e). Unlike the retrofitted 2-ft-tall specimens, a more definitive pattern of the behavior of the nails was evident: at the top of the plywood, the nails would withdraw, and at the bottom the nails would pull through. At the bottom corners, the plywood bore down on the sill plate and end studs, causing incipient crushing of the panels; see Figure 4.20(f).

(a)



(b)

Figure 4.19 Specimen A-26 pre-test photographs for the retrofitted 6-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition “c”: (a) exterior elevation; (b) interior elevation; (c) south-end corner of wall view; and (d) south-end exterior corner of wall view.

(c) (d)

Figure 4.19 (continued).

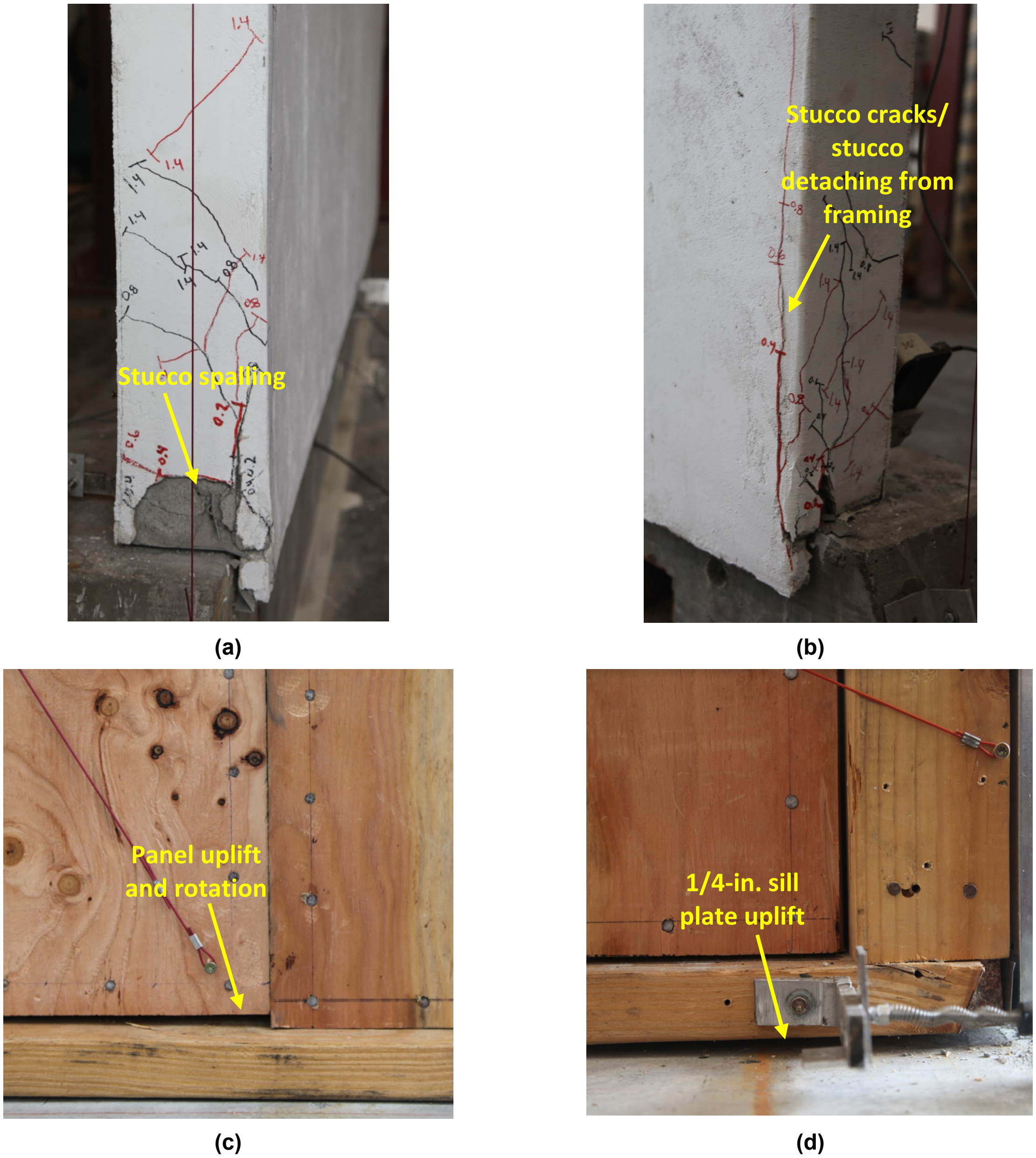
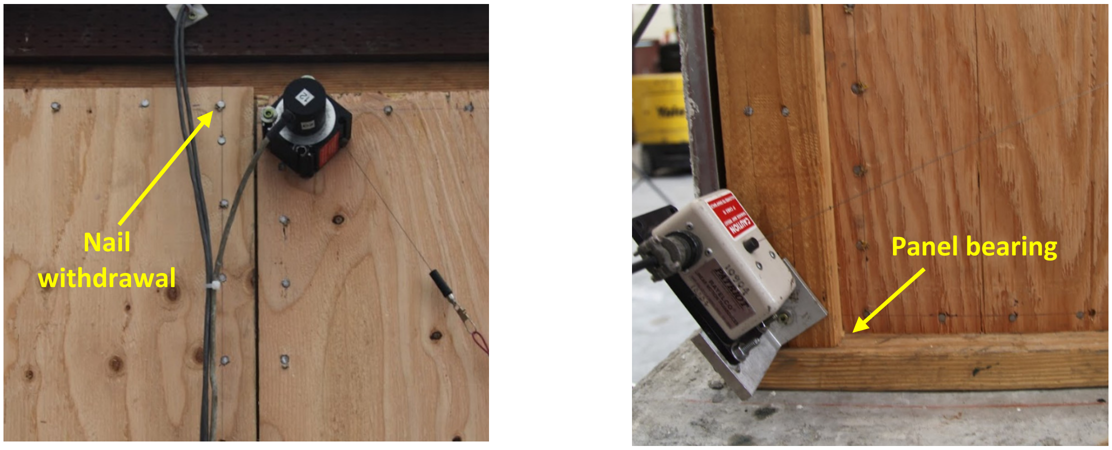


Figure 4.20 Specimen A-26 damage state at -1.4% drift ratio @ Δ = -1.008 in.: (a) bottom of south-end exterior corner of wall view; (b) bottom of north-end exterior corner of wall view; (c) bottom interior of wall view (south and middle panels); (d) bottom of south-end interior of wall view; (e) top interior of wall view (north and middle panels); and (f) bottom of north-end corner of wall view.



(e) (f)

Figure 4.20 (continued).

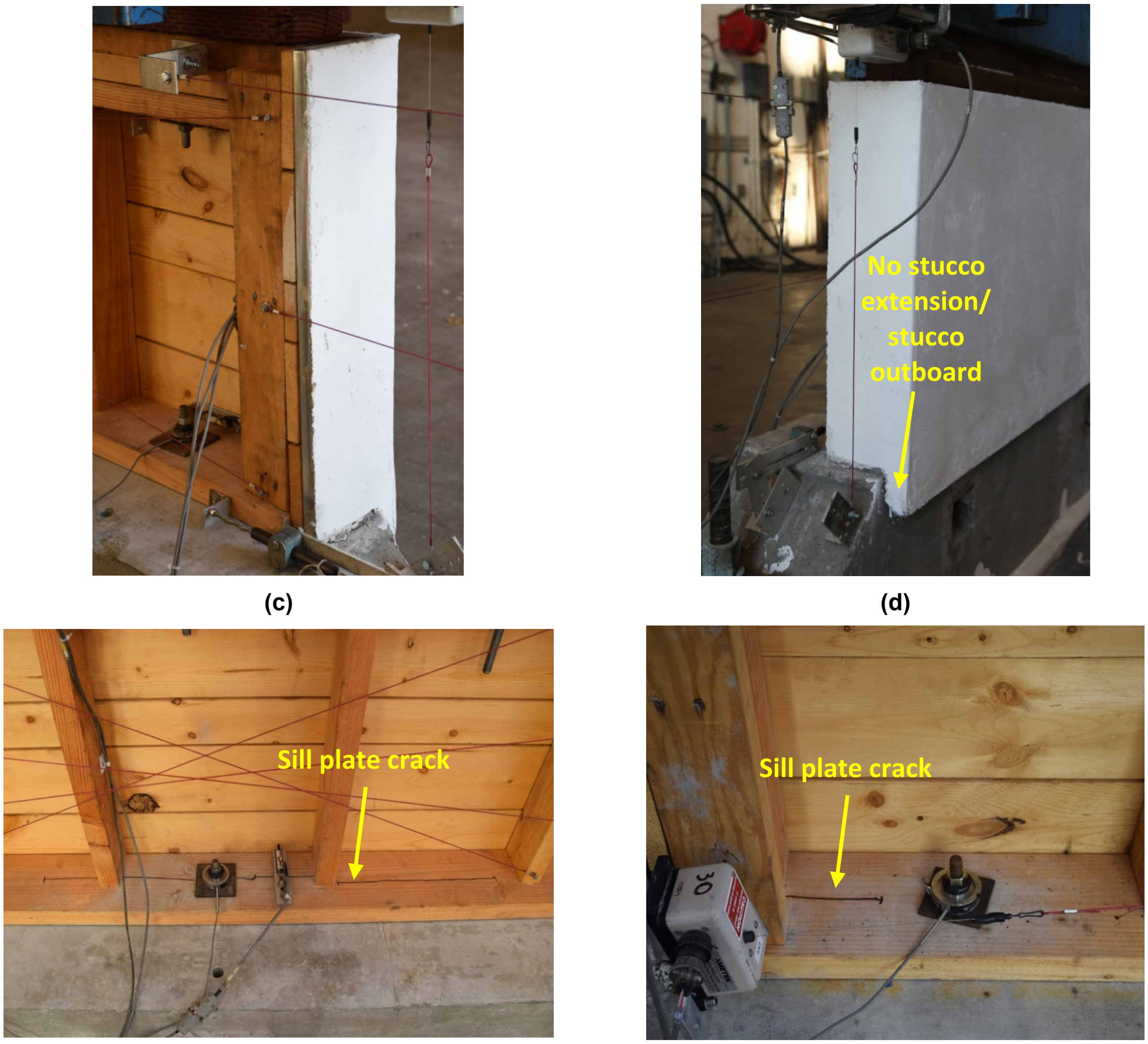
4.2.11 Specimen A-27 0.0% to 1.4% Drift Ratio Level

The photographs in Figure 4.21 show Specimen A-27 prior to testing. Specimen A-27 was an existing 2-ft-tall cripple wall with stucco over horizontal sheathing exterior finish and bottom boundary condition "c". The horizontal sheathing was made of 1 × 6 Douglas Fir boards. As with the other horizontal sheathing finished specimens, the top and bottom boards were full size, and the middle board was cut-to-fit. Specimen A-27 was loading monotonically. It was the only specimen to be loaded monotonically in this program. The finish materials, boundary conditions, retrofit condition, and height were selected based on them being the most commonly tested in this program. There was no pre-existing damage to the stucco prior to testing. On the interior however, cracks had formed along the sill plate. One crack developed on the north end [Figure 4.12(f)], and a series of cracks had formed through the middle; see Figure 4.12(e). These cracks were less than 1/32 in. thick and developed during the curing process of the stucco, which dried out the sill plate. The damage incurred by this test will be discussed in Section 4.4.

(a)

(b)

Figure 4.21 **Specimen A-27 pre-test photographs for the existing 2-ft-tall cripple wall with stucco over framing exterior finish and bottom boundary condition "c", monotonic loading: (a) exterior elevation; (b) interior elevation; (c) south-end interior corner of wall view; and (d) south-end exterior corner of wall view; (e) bottom of middle interior of wall view; and (f) bottom of north-end interior of wall view.**



(c) (d)

(e) (f)

Figure 4.21 (continued).

4.3 Damage Characteristics at Lateral Strength

Beyond the low levels of drift, another key damage state occurs at attainment at lateral strength of each cripple wall. Thus, the damage features presented in this section are those that occurred following attainment of the lateral strength of the cripple walls and beyond where larger imposed drifts resulted in a loss of load capacity. Examining the damage states at this level provides insight as to how and why failure occurs in a cripple wall. It is noted that lateral strength for all eleven cripple walls tested occurred between global drift ratios of 1.4–8.0% and relative drift ratios of 1.0–5.3%. The relative drift is defined as the drift of the cripple wall only, absent displacement of the sill plate relative to the foundation.

4.3.1 Specimen A-15 Lateral Strength

Figure 4.22 shows the damage state of Specimen A-15 at lateral strength. Lateral strength occurred at 4% global drift ratio in the push loading direction and 5% global drift ratio in the pull loading direction. The relative drift ratio at strength was 2.5% in the push loading direction and 2.1% in the pull loading direction. Figure 4.22(a) and (b) shows the cracking patterns on the corners of the cripple wall; additional cracks formed across the exterior face of the specimen as well. Strength was reached when a cross-grain crack formed at both ends of the sill plate; see Figure 4.22(f). The cracks propagated through the anchor bolt holes in the sill plate, leading to a drop in capacity in subsequent drift cycles as the anchor bolts were no longer able to restrain the sill plate from displacing. Had the sill plate remained intact, the capacity of the specimen would have continued to increase. There was no evidence that the stucco had fully detached from the furring nails along the sill plate or studs, i.e., the stucco could have continued to provide increases in strength. In addition, the load was symmetric between both directions of loading, which was not expected for specimens with diagonal sheathing. Typically, the orientation of the sheathing boards would provide a substantial increase in the strength in the pull loading direction compared with the push loading direction. This is caused by the gaps between the boards closing when loaded in the pull direction (as opposed to opening in the push direction), which did not occur during testing; see Figure 4.22(f).

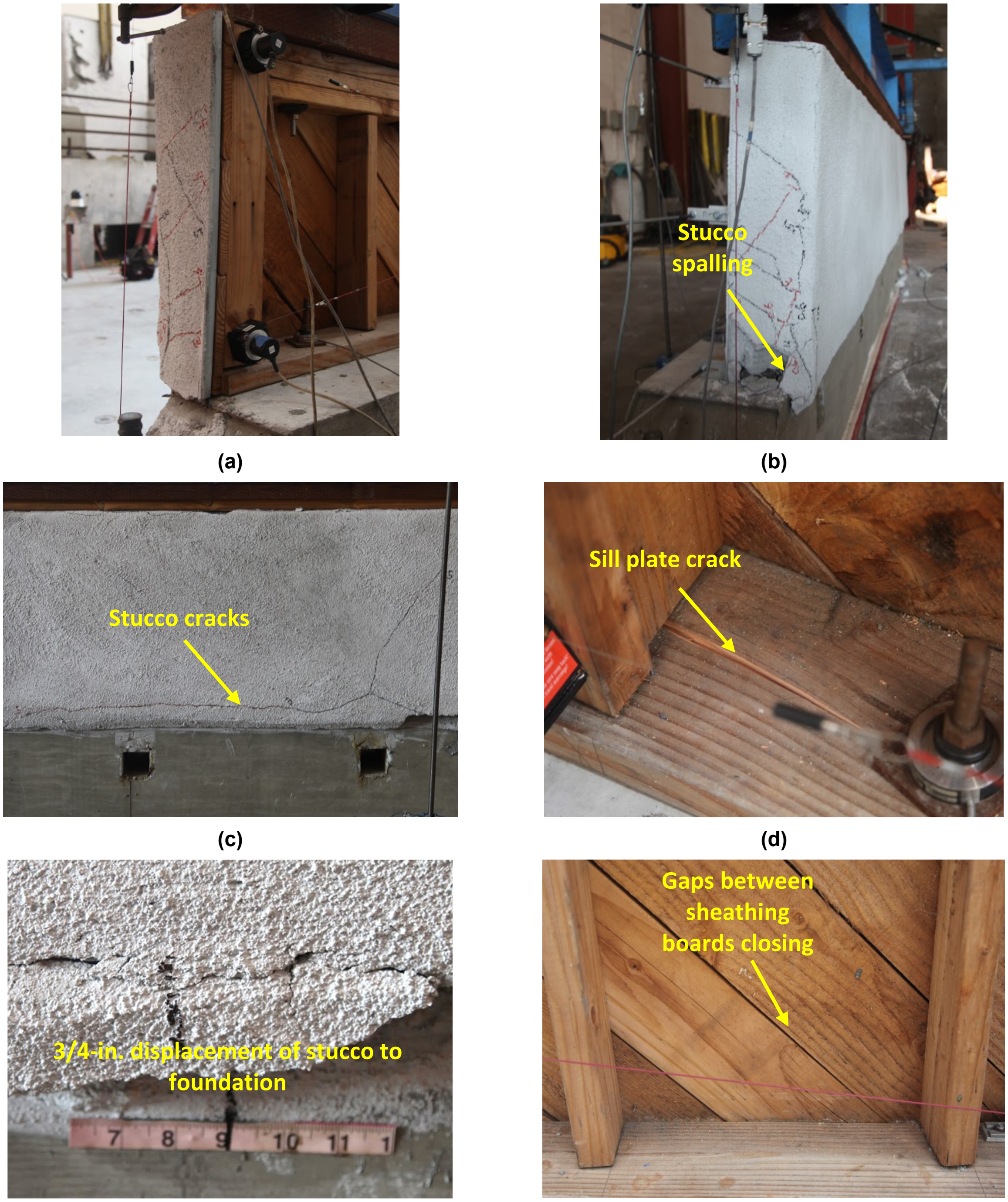


Figure 4.22 Specimen A-15 damage state at lateral strength at +5% drift ratio @ Δ = +1.20 in. unless otherwise noted: (a) north-end interior corner of wall view; (b) south-end exterior corner of wall view; (c) middle exterior of wall view; (d) bottom of north-end interior of wall view; (e) bottom of north-end exterior of wall view; and (f) bottom of middle interior of wall view at -4% drift.

4.3.2 Specimen A-16 Lateral Strength

Figure 4.23 shows the damage state of Specimen A-16 at lateral strength. Lateral strength occurred at 4% global drift ratio in the push loading direction and 5% global drift ratio in the pull loading direction. The relative drift ratio at strength was 2.2% in the push loading direction and 2.1% in the pull loading direction. The strength was inhibited due to fractures in all anchor bolts. From Figure 4.23(b) and (c), it is evident that the sill plate experienced a 1-in. displacement along the foundation. Multiple diagonal cracks formed across the exterior face of the stucco in the pull loading direction. This is a result of the orientation of the sheathing boards, which ran in the same direction as the cracks. The imposed displacement in the push loading direction caused the sheathing boards to uplift and separate, which in turn put tensile stresses on the stucco face, resulting in the cracking pattern shown in Figure 4.23(a). There was minimal damage to the plywood panels at strength. No nails had torn through the plywood edges, withdrew from the framing, or pulled through the plywood, which would have occurred if the plywood panels had been fully mobilized. Therefore, the strength capacity of the cripple wall was significantly reduced by the fracturing of the anchor bolts.

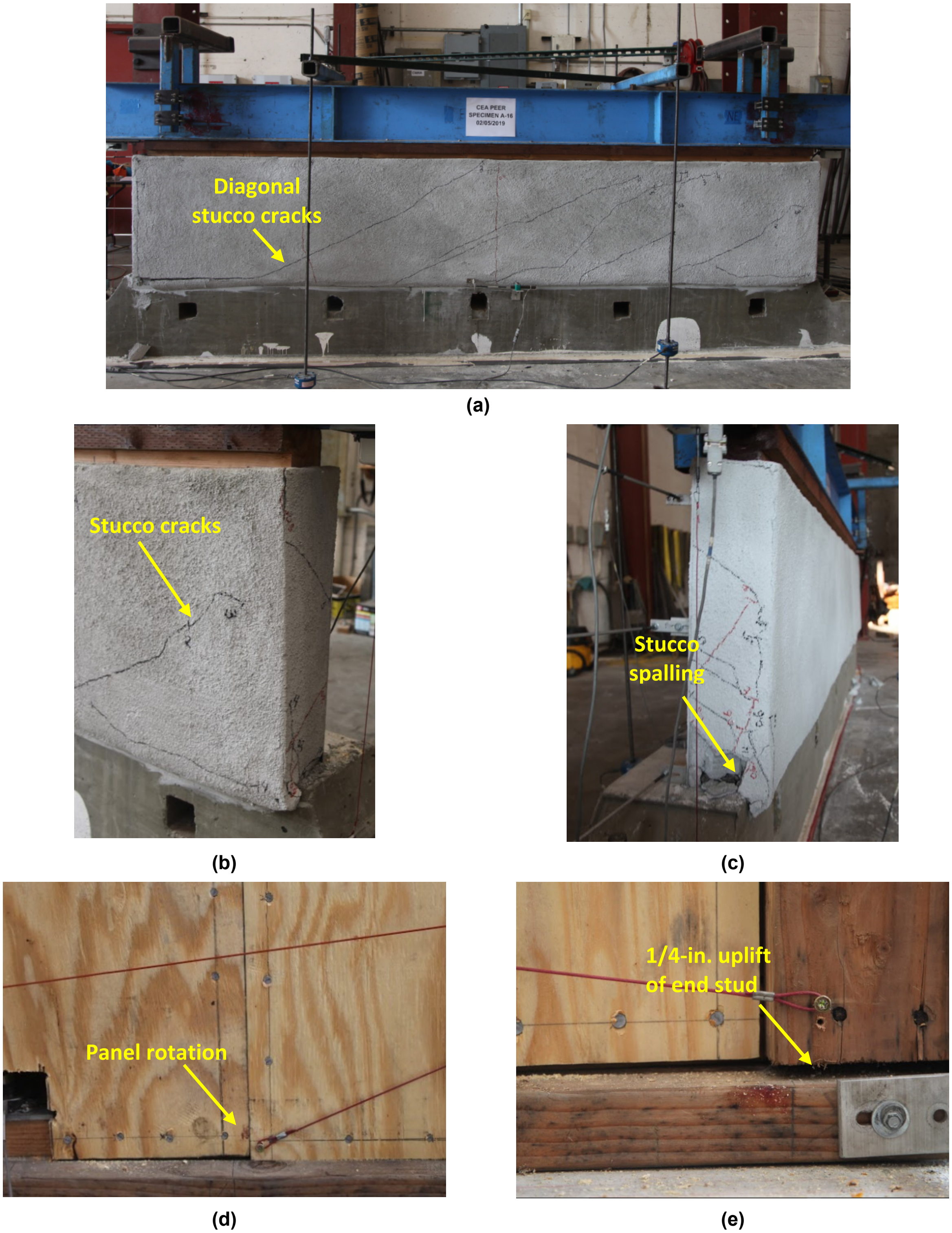
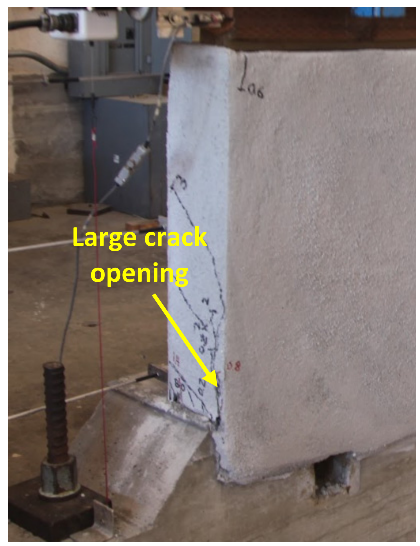


Figure 4.23 Specimen A-16 damage state at lateral strength at -5% drift ratio @ Δ = -0.96 in.: (a) exterior elevation; (b) north-end exterior corner of wall view; (c) south-end exterior corner of wall view; (d) bottom interior of wall view (south and middle panels); and (e) bottom of south-end interior of wall view.

4.3.3 Specimen A-17 Lateral Strength

Figure 4.24 shows the damage state of Specimen A-17 at lateral strength. Lateral strength occurred at 3% global drift ratio in the push loading direction and 2% global drift ratio in the pull loading direction. The relative drift ratio at strength was 1.7% in the push loading direction and 1.2% in the pull loading direction. At lateral strength, the stucco had detached from the furring nails at the sill plate as well as partially detached from the furring nails at the bottom of the studs. This is shown by the large crack openings at the corners of the walls [Figure 4.24(a) and (b)] as well as the out-of-plane displacement of the stucco at the base of the cripple wall; see Figure 4.24(e) and (f). Throughout the interior of the wall, there was little damage to the framing; see Figure 4.24(c) and (d). Since stucco is essentially a rigid body and once the furring nails detach at the sill plate, an abrupt drop in capacity in the subsequent drift cycles occurred as the furring nails were the only fasteners transferring the lateral load.

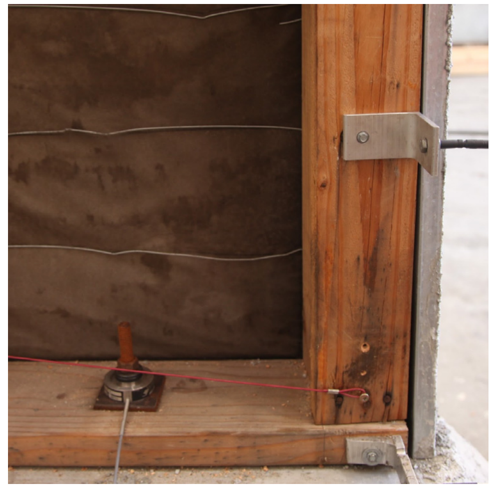
(a)



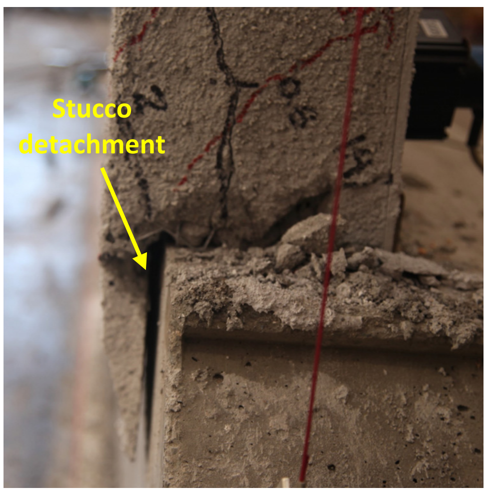
(b)

Figure 4.24 Specimen A-17 damage state at lateral strength at -3% drift ratio @ Δ = -0.72 in.: (a) north-end exterior corner of wall view; (b) south-end exterior of wall view; (c) bottom of north-end corner of wall view; (d) bottom of north-end interior of wall view; (e) bottom of north-end corner of wall view; and (f) bottom of south-end corner of wall view.

(c)



(d)



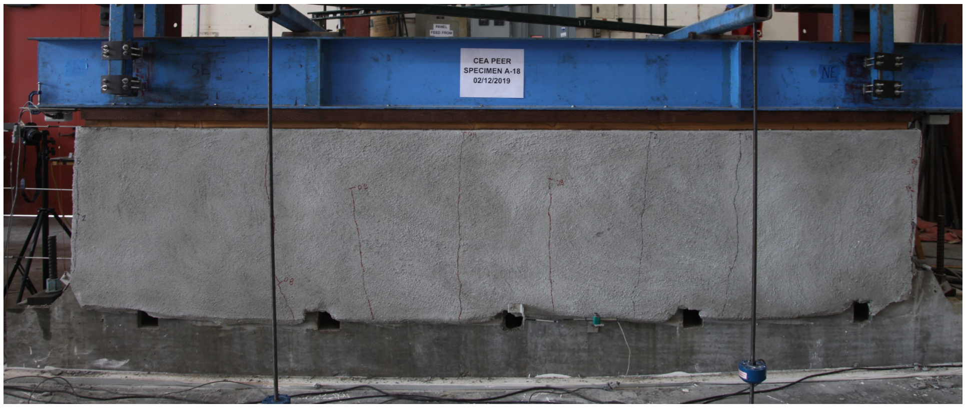
(e)

(f)

Figure 4.24 (continued).

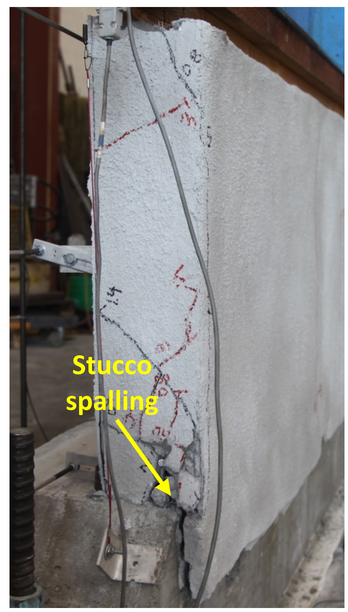
4.3.4 Specimen A-18 Lateral Strength

Figure 4.25 shows the damage state of Specimen A-18 at lateral strength. Lateral strength occurred at 6% global drift ratio in the push loading direction and 6% global drift ratio in the pull loading direction. The relative drift ratio at strength was 4.5% in the push loading direction and 5.0% in the pull loading direction. The addition of the retrofit significantly increased the drift capacity of the cripple wall. This is due to the improved connection of the fasteners attached the plywood to the framing compared with the furring nails that attached the stucco to the framing. Along the face of the cripple wall, multiple vertical cracks formed, as shown in Figure 4.25(a). The stucco had detached from the furring nails at the sill plate and bottom of the studs, which is shown by the gap that formed between the stucco extension and the footing, i.e., out-of-plane displacement of the stucco; see Figure 4.25(f) and (g). Along the interior of the cripple wall, the plywood panels had significantly rotated [Figure 4.25(d)], and there was crushing of the panels against the flat studs see Figure 4.25(e). While the fasteners connecting the plywood to the framing had not yet pulled through the plywood or withdrew from the framing, they were heavily rotated and showed signs incipient withdrawal or pull through. A 1/2-in. uplift occurred at the ends of the panels and corner studs, as shown in Figure 4.25(b).



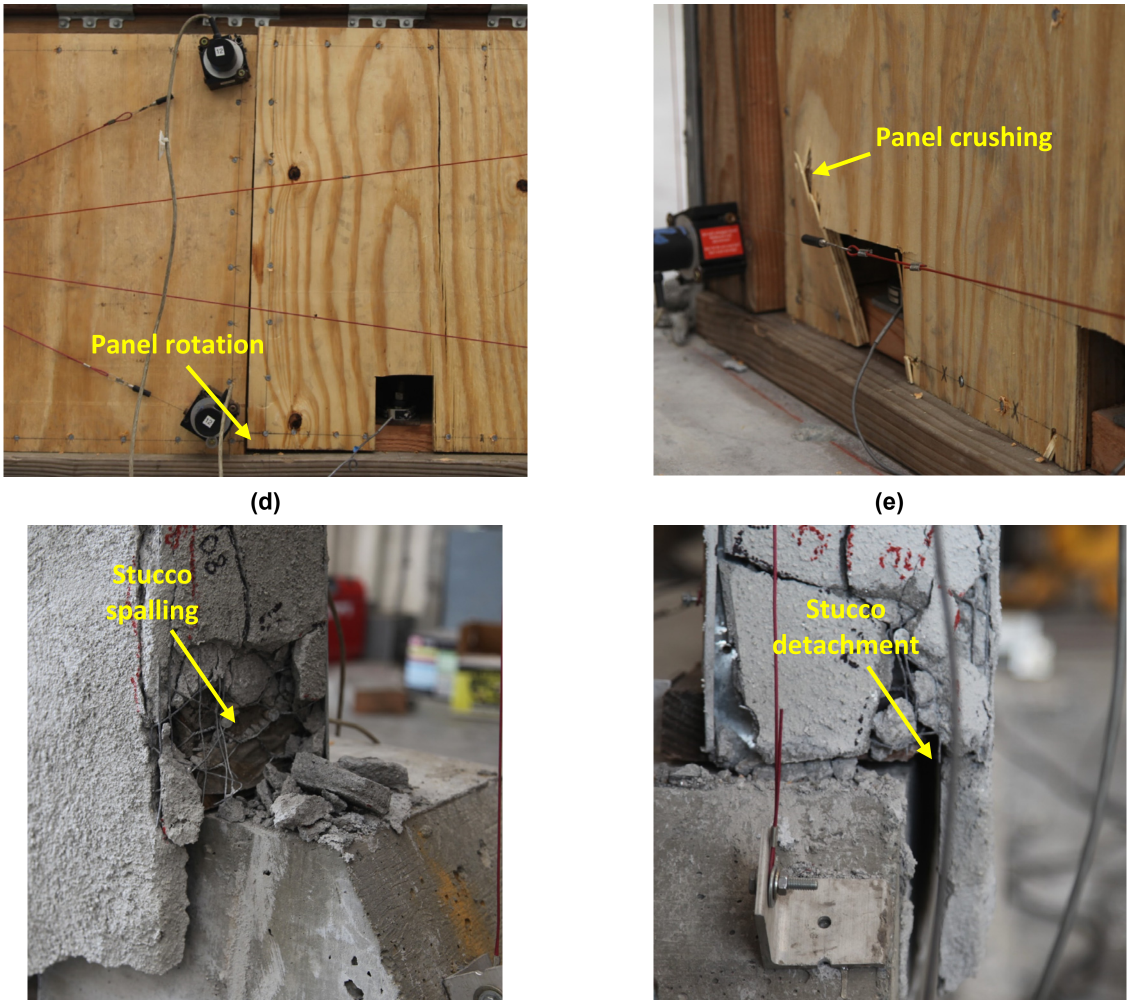
(a)

(b)



(c)

Figure 4.25 Specimen A-18 damage state at lateral strength at -6% drift ratio @ Δ = -1.44 in.: (a) exterior elevation; (b) south-end interior of wall view; (c) south-end interior corner of wall view; (d) interior of wall view (south and middle panels); (e) bottom of north-end interior corner of wall view; (f) bottom of north-end exterior corner of wall view; and (g) bottom of south-end corner of wall view.



(d) (e)

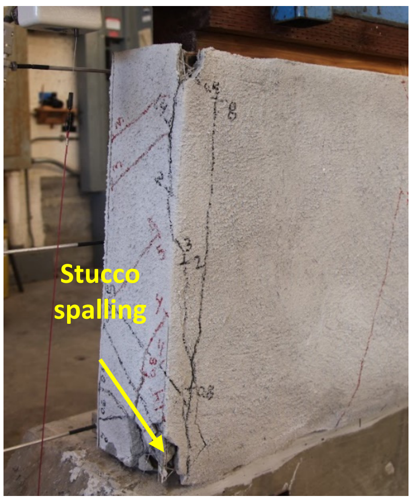
(f) (g)

Figure 4.25 (continued).

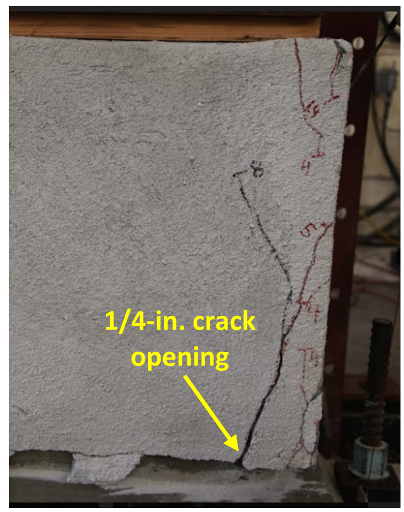
4.3.5 Specimen A-19 Lateral Strength

Figure 4.26 shows the damage state of Specimen A-19 at lateral strength. Lateral strength occurred at 8% global drift ratio in the push loading direction and 8% global drift ratio in the pull loading direction. The relative drift ratio at strength was 5.3% in the push loading direction and 5.3% in the pull loading direction. At strength, multiple cracks had formed in the stucco along the exterior face of the specimen; see Figure 4.26(a). Most of the cracks propagated vertically, with the largest crack openings occurring near both corners of the cripple wall; see Figure 4.26(b) and (c). The crack openings were as large as a 1/4 in wide, which indicates that the stucco had detached from the furring nails at the sill plate and bottom of the studs. On the interior of the cripple wall, ½ in. uplift of the plywood and corner studs had occurred at the ends of the specimens. The uplift caused splitting of the blocking at the end stud bays; see Figure 4.26(d). The plywood panels were crushed due to bearing on the flat studs at both ends of the specimen as well see Figure 4.26(e). The panels exhibited large rotations as shown in Figure 4.26(f). Many of the nails showed incipient pull through at the bottom and sides of the panels, and some of the nails had torn through the edges near the locations of the anchor bolts see Figure 4.26(g).

(a)

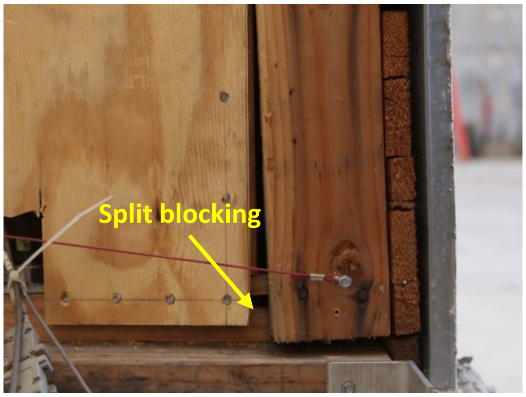


(b)

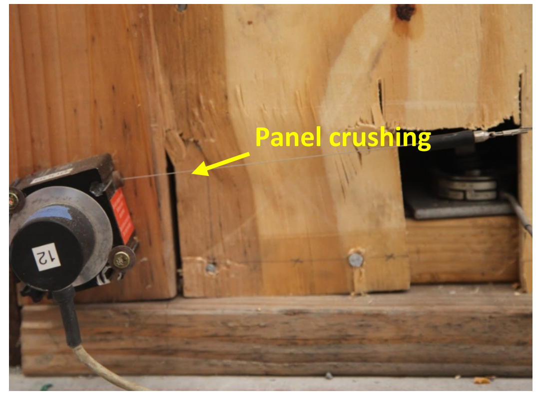


(c)

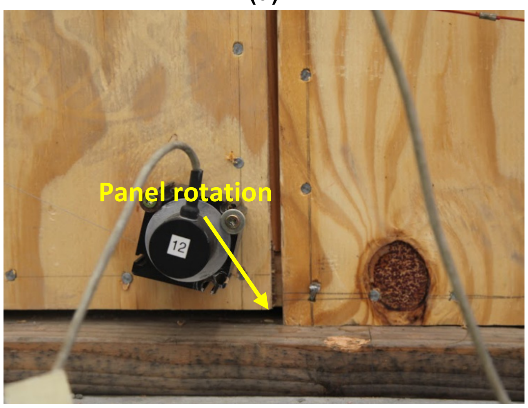
Figure 4.26 **Specimen A-19 damage state at lateral strength at +8% drift ratio @ Δ = +1.92 in. : (a) exterior elevation; (b) south-end exterior corner of wall view; (c) north-end exterior of wall view; (d) bottom interior of wall view (south and middle panels); (e) bottom interior of wall view (north panel); (f) bottom interior of wall view (south and middle panels); and (g) bottom interior of wall (north panel).**



(d)



(e)



(f)

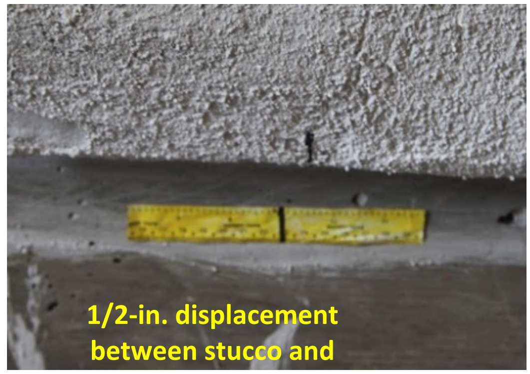
(g)

Figure 4.26 (continued).

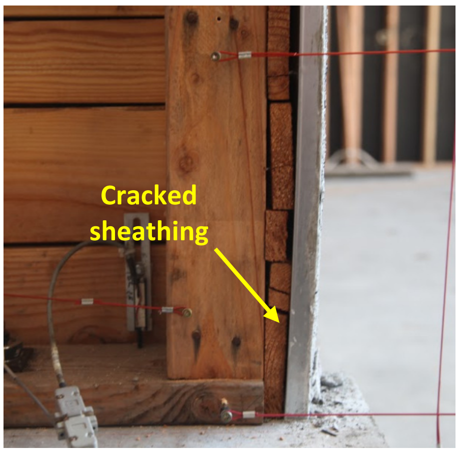
4.3.6 Specimen A-20 Lateral Strength

Figure 4.27 shows the damage state of Specimen A-20 at lateral strength. Lateral strength occurred at 3% global drift ratio in the push loading direction and 3% global drift ratio in the pull loading direction. The relative drift ratio at strength was 2.4% in the push loading direction and 2.4% in the pull loading direction. At strength, the stucco had detached from the furring nails at the sill plate and bottom of the studs, which occurred in all wet finished cripple walls. This can be seen by the gap that formed between the stucco extension and the footing shown in Figure 4.27(f). At the top of the cripple wall, the stucco and sheathing had displaced a 1/4 in. relative to the framing; a 1/2-in. displacement occurred at the bottom of the finish material and the foundation; see Figure 4.27(a) and (b). Many of the sheathing board at the corners had split due to the bearing of the finish materials at the corners on the foundation; see Figure 4.27(c). The stucco detached from the sheathing nails as well but remained attached to the furring nails; see Figure 4.27(d). Typically, the furring nails would remain attached to the sheathing/framing, but due to the cracks in the sheathing boards, there was less resistance to the furring nails withdrawing from the sheathing/framing.

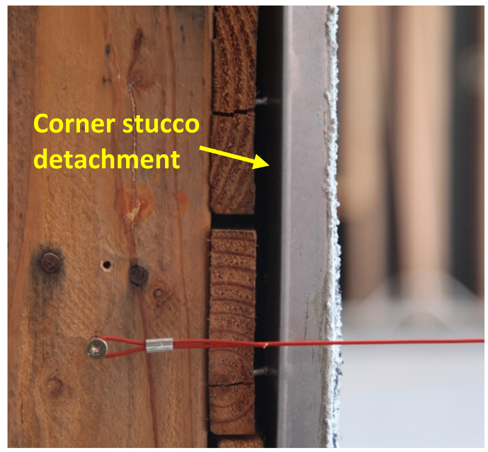
(a)



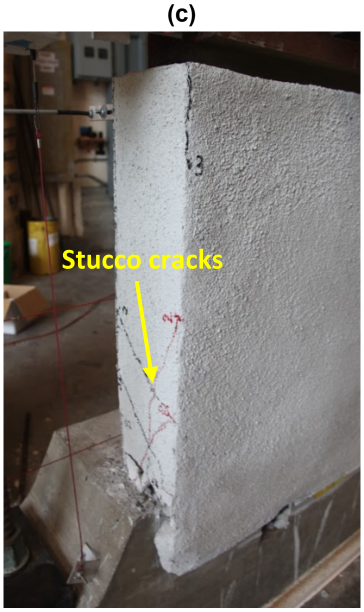
(b)



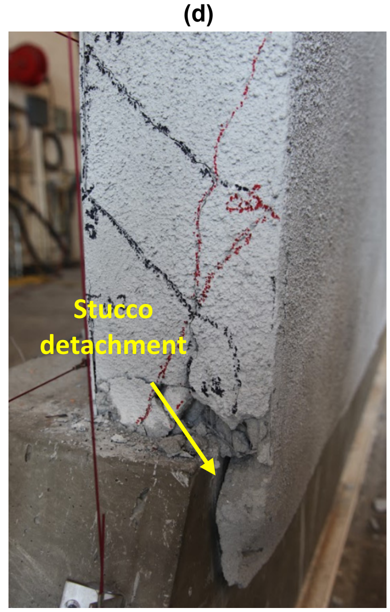
(c)



(d)



(e)



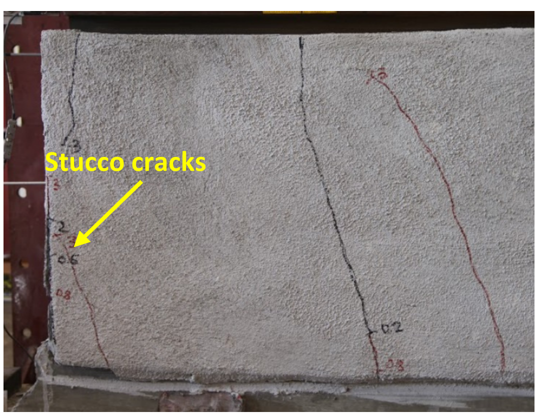
(f)

Figure 4.27 Specimen A-20 damage state at lateral strength at +3% drift ratio @ Δ = +0.72 in.: (a) top of north-end exterior of wall view; (b) bottom of north-end exterior of wall view; (c) bottom of south-end interior corner of wall view; (d) middle of south-end interior corner of wall view; (e) south-end corner of wall view; and (f) bottom of south-end corner of wall view.

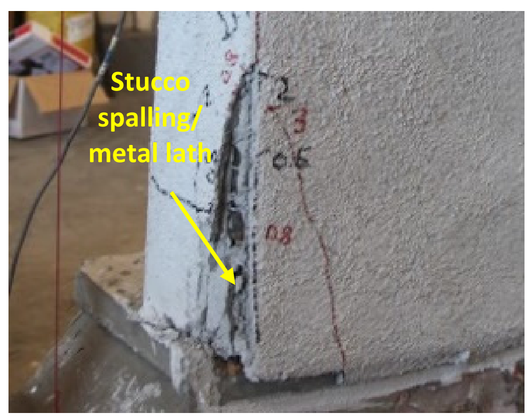
4.3.7 Specimen A-21 Lateral Strength

Figure 4.28 shows the damage state of Specimen A-21 at lateral strength. Lateral strength occurred at 3% global drift ratio in the push loading direction and 3% global drift ratio in the pull loading direction. The relative drift ratio at strength was 3.0% in the push loading direction and 2.0% in the pull loading direction. Multiple vertical cracks formed in the stucco across the exterior face cripple wall at strength; see Figure 4.28(a). The largest cracks formed at the base and propagated upward. These cracks indicate that the stucco had detached from the furring nails at the sill plate and base of the studs; see Figure 4.28(b) and (c). More spalling of the stucco occurred with this specimen than any of the other existing cripple walls tested. This is likely due to the wet set sill condition that inhibited any movement of the sill plate relative to the foundation, causing the exterior face of the stucco to displace while the corners could not. Along the interior of the specimen, cracks had formed at the top of some of the end studs [Figure 4.28(e)], and the studs had rotated considerably; see Figure 4.28(f). The sheathing boards along the exterior face remained intact at this point.

(a)

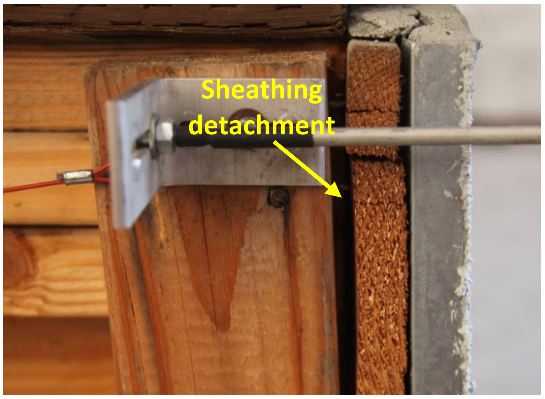


(b)

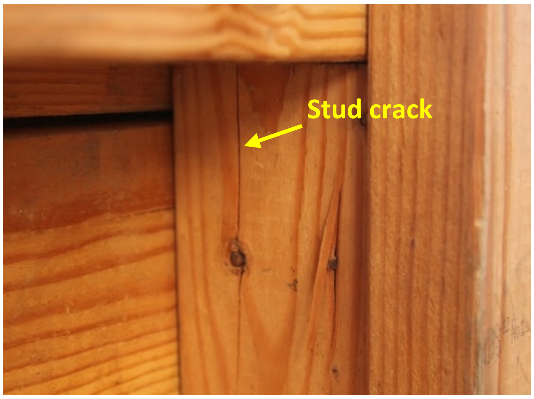


(c)

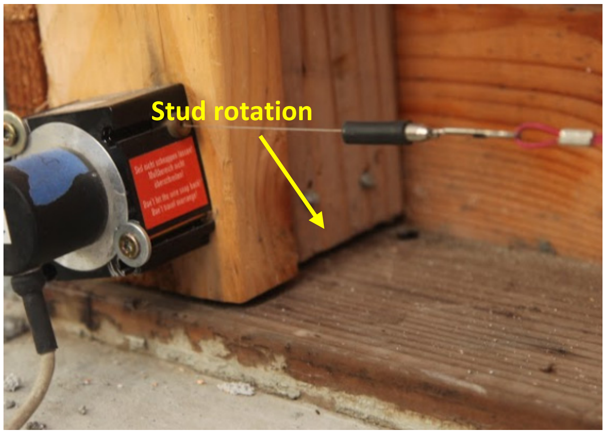
Figure 4.28 **Specimen A-21 damage state at lateral strength at +3% drift ratio @ Δ = +0.72 in.: (a) exterior elevation; (b) south-end exterior of wall view; (c) bottom of south-end exterior corner of wall view; (d) top of south-end interior corner of wall view; (e) top of south-end interior of wall view; and (f) bottom of north-end interior of wall view.**



(d)



(e)

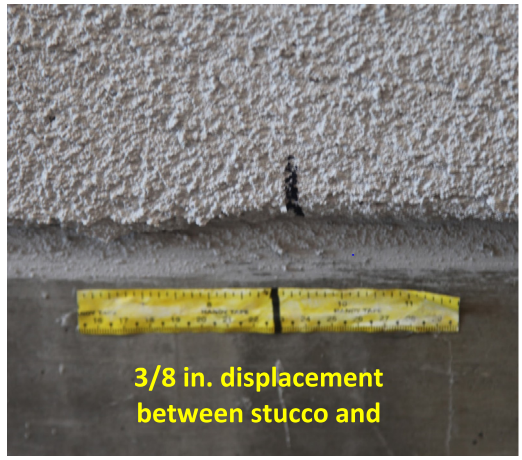


(f)

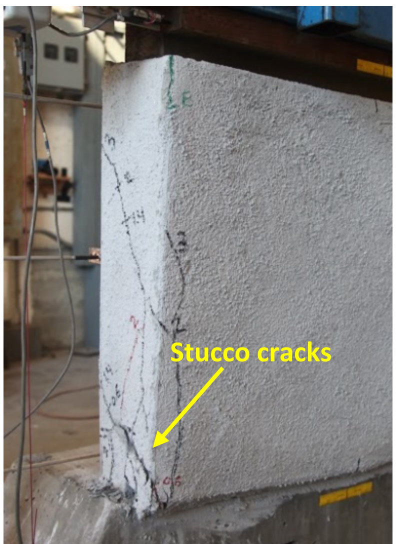
Figure 4.28 (continued).

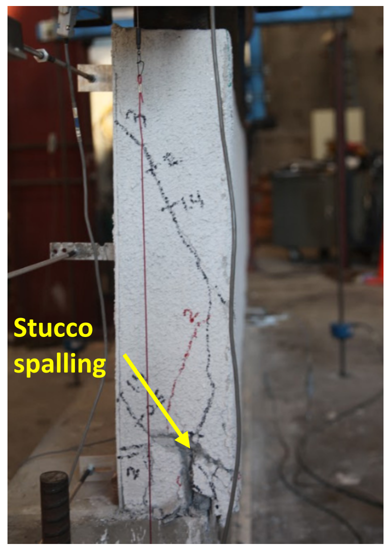
4.3.8 Specimen A-22 Lateral Strength

Figure 4.29 shows the damage state of Specimen A-22 at lateral strength. Lateral strength occurred at 2% global drift ratio in the push loading direction and 2% global drift ratio in the pull loading direction. The relative drift ratio at strength was 1.1% in the push direction and 1.3% in the pull direction. The damage to this specimen was nearly identical to that of Specimen A-17 which differed only in the boundary condition at the bottom of the cripple wall. At strength, large cracks formed at both corners of the cripple wall, once again indicating the stucco had detached from the furring nails at the sill plate and bottom of the studs; see Figure 4.29(c) and (d). The detachment of the stucco from the furring nails can better be seen in Figure 4.29(f) which shows the sill plate from the interior side of the cripple wall. Besides the cracks concentrated at the corners, there were no other cracks that had formed across the exterior face of the specimen. There was no displacement of the stucco relative to the framing at the top of the wall; see Figure 4.29(a) and 3/8-in. displacement of the stucco relative to the foundation at the bottom of the wall; see Figure 4.29(b). One of the studs on the interior of the cripple wall formed a large crack, as shown in Figure 4.29(e), but the rest of the framing was not damaged.

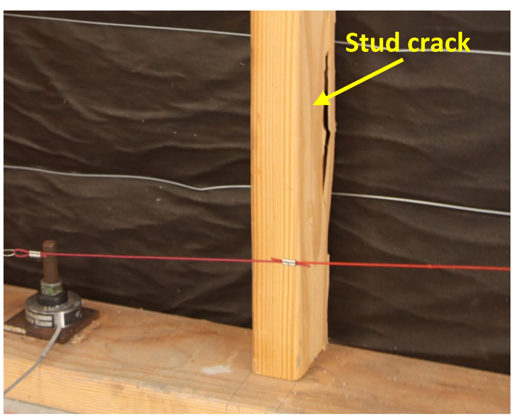


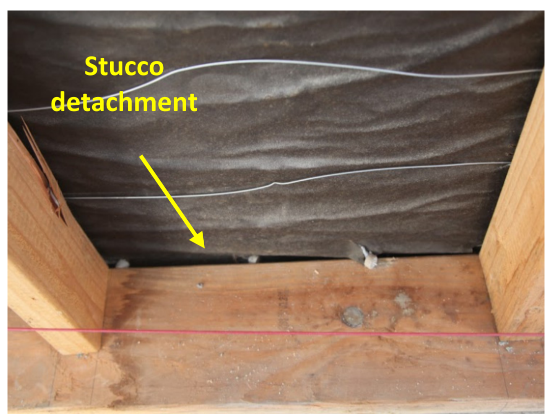
(a) (b)





(c) (d)



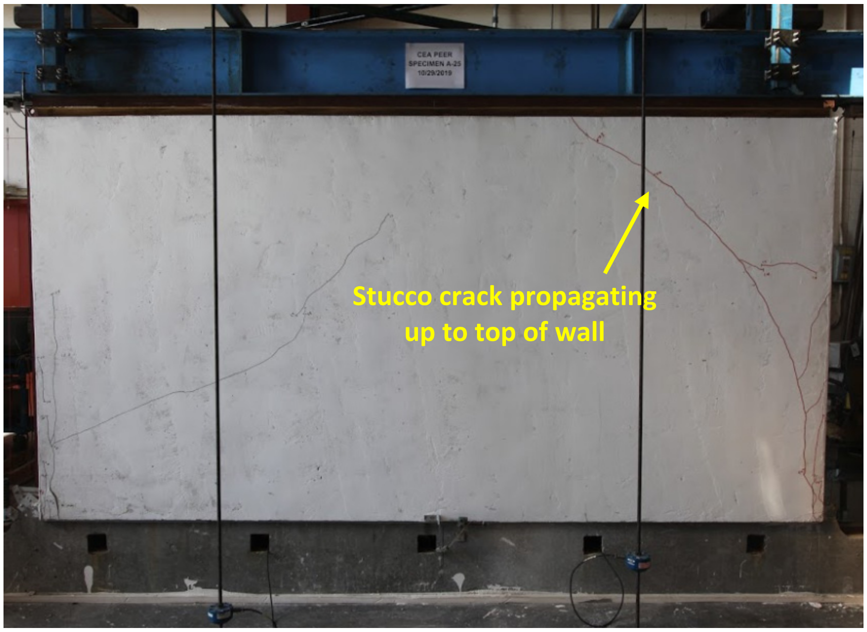


(e) (f)

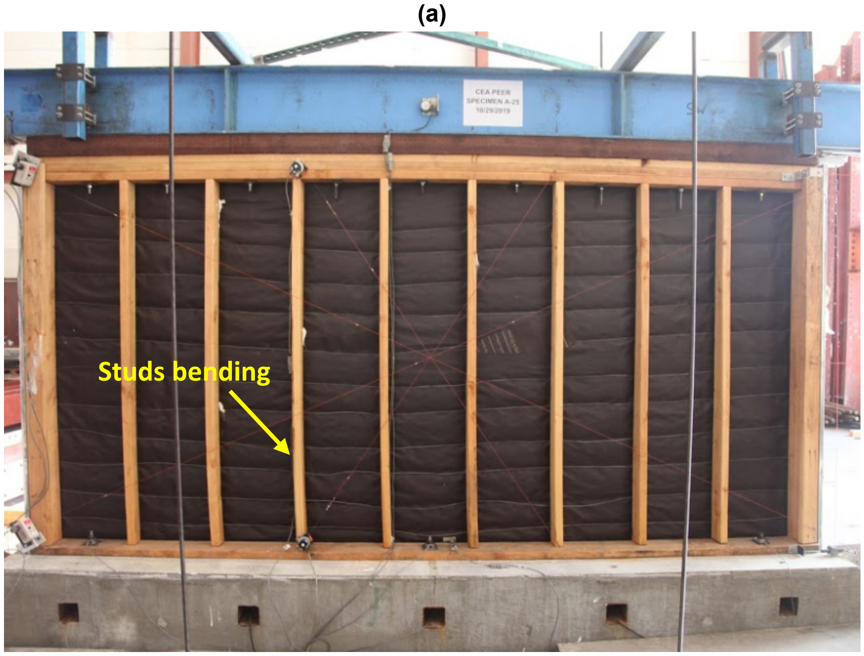
Figure 4.29 Specimen A-22 damage state at lateral strength at -2% drift ratio @ Δ = -0.48 in.: (a) top of north-end exterior of wall view; (b) bottom of north-end exterior of wall view; (c) south-end exterior corner of wall view; (d) south-end corner of wall view; (e) bottom of middle interior of wall view; and (f) bottom middle interior of wall view.

4.3.9 Specimen A-25 Lateral Strength

Figure 4.30 shows the damage state of Specimen A-25 at lateral strength. Lateral strength occurred at 1.4% global drift ratio in the push loading direction and 1.4% global drift ratio in the pull loading direction. The relative drift ratio at strength was 1.0% in the push loading direction and 1.1% in the pull loading direction. Large diagonal cracks had extended across the exterior face of the specimen; see Figure 4.30(a). The largest crack openings were vertical cracks that had formed at the bottom and propagated upward at both ends of the specimen, as seen in Figure 4.30(f). 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 photograph of the interior, as shown in Figure 4.30(c). Heavy spalling of the stucco occurred at both corners, which is primarily due to the corners bearing on the foundation; see Figure 4.20(d) and (e). Along the interior, there was visible bending of the studs, which had not been seen with any of the 2-ft-tall cripple walls; see Figure 4.30(b). The flexure in the studs occurred in this specimen and not any of the other 2-ft-tall specimens because the increased height caused the failure to be more flexure dominated than shear dominated.

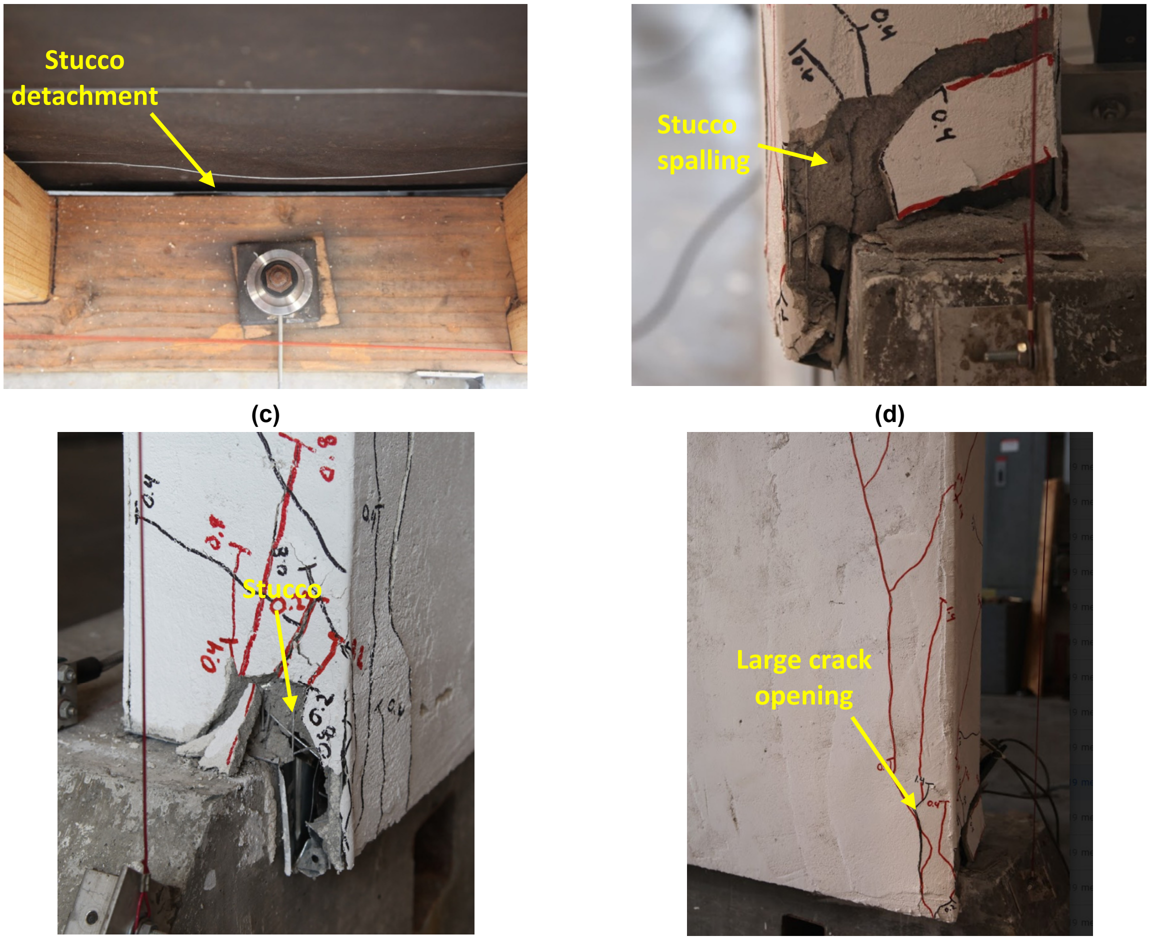


(a)



(b)

Figure 4.30 **Specimen A-25 damage state at lateral strength at -1.4% drift ratio @ Δ = -1.008 in.: (a) exterior elevation; (b) interior elevation; (c) bottom of middle interior of wall view; (d) bottom of south-end corner of wall view; (e) bottom of south-end exterior corner of wall view; and (f) bottom of north-end exterior of wall view.**



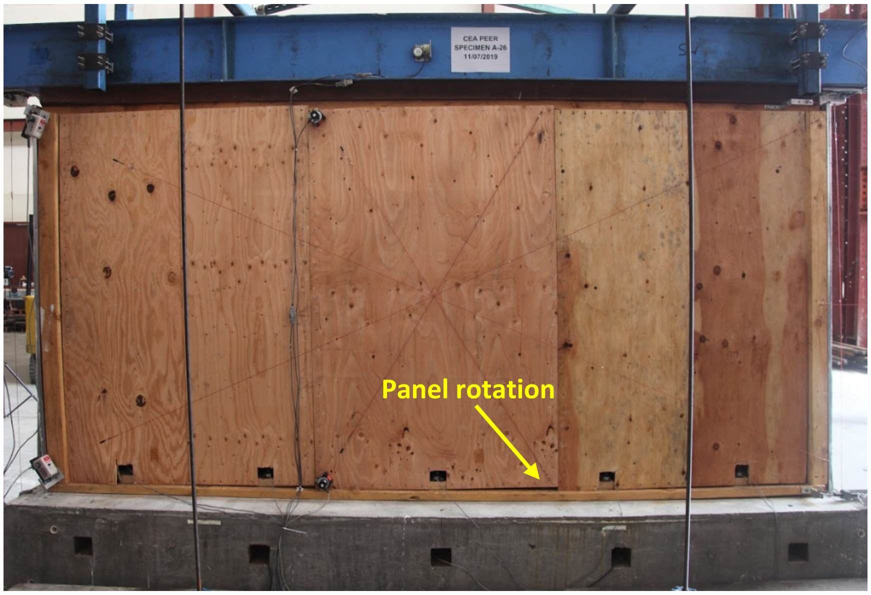
(c) (d)

(e) (f)

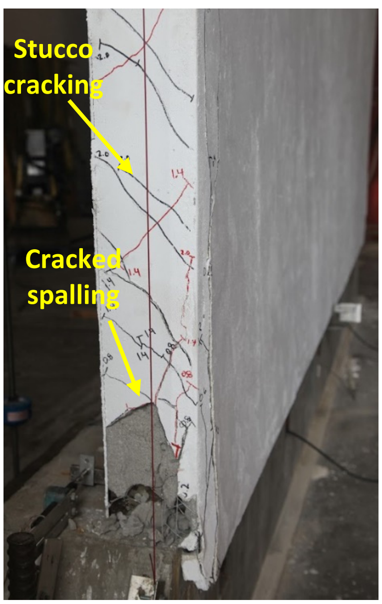
Figure 4.30 (continued)

4.3.10 Specimen A-26 Lateral Strength

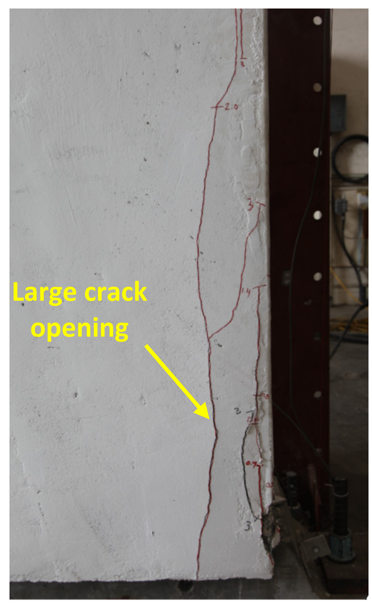
Figure 4.31 shows the damage state of Specimen A-26 at lateral strength. Lateral strength occurred at 3% global drift ratio in the push loading direction and 3% global drift ratio in the pull loading direction. The relative drift ratio at strength was 2.9% in the push loading direction and 2.9% in the pull loading direction. Figure 4.31(a) shows the rotation of the plywood panels. As with the existing specimen, large cracks had formed in the stucco at the ends of the exterior face, starting from the bottom and propagating upward; see Figure 4.31(c). 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, with much of the stucco having spalled off; see Figure 4.31(b) and (e). The stucco had also detached from the framing at the bottom of both corners. Along the interior, the plywood panels had crushed due to bearing on the flat studs, as shown in Figure 4.31(d). Uplift of both the sill plate and the plywood panels occurred. The sill plate was bent at the ends of the cripple walls, as seen in Figure 4.31(g). 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. Many of the nails showed incipient pull through at the bottom of the cripple wall and incipient withdrawal at the top; see Figure 4.31(f).



(a)

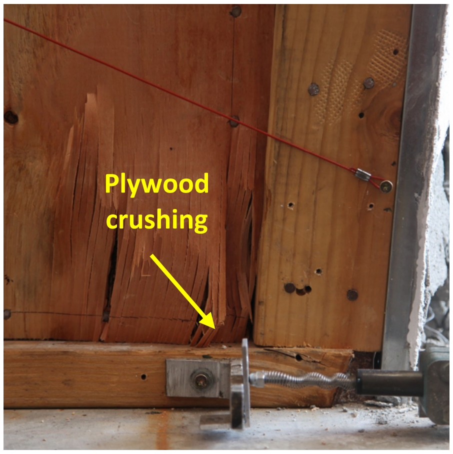


(b)

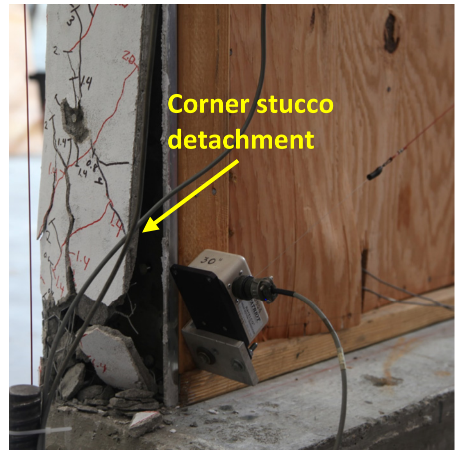


(c)

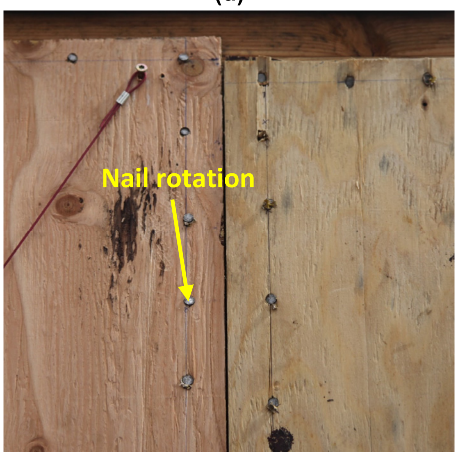
Figure 4.31 Specimen A-26 damage state at t lateral strength (-3% drift ratio, Δ = -2.16 in.) unless otherwise noted: (a) interior elevation; (b) bottom of south-end exterior corner of wall view; (c) bottom of north-end exterior corner of wall view; (d) bottom of south-end interior of wall view at +3% drift; (e) bottom of north-end interior corner of wall; (f) top interior of wall view at +3% drift (north and middle panels); and (g) bottom of north-end interior of wall view at +3% drift.



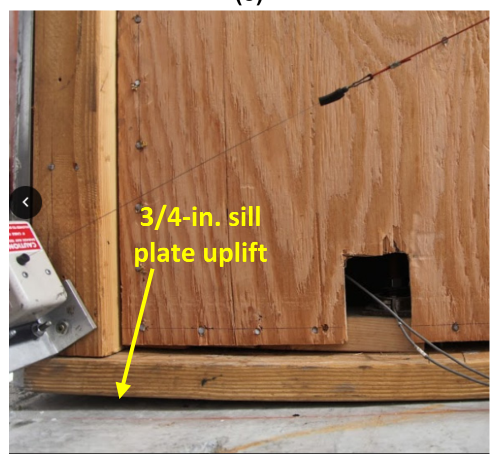
(d)



(e)



(f)



(g)

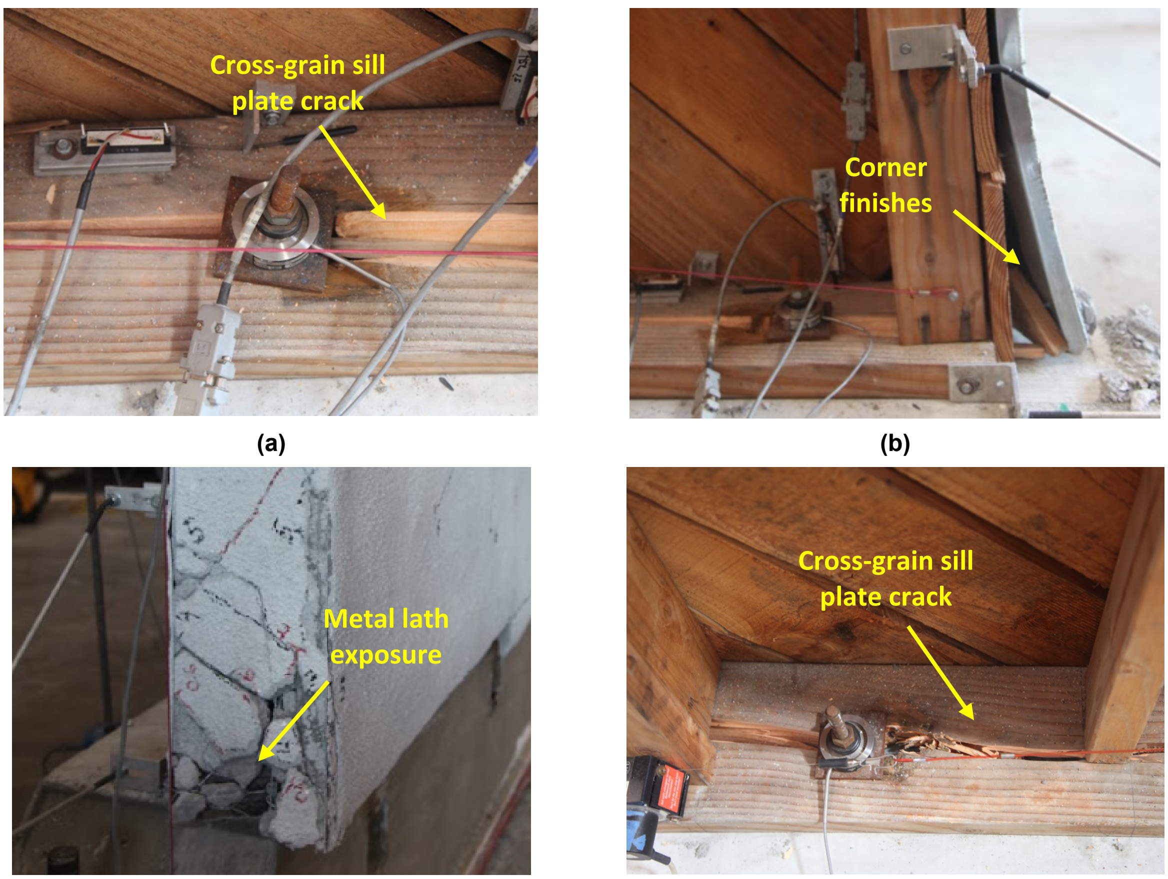
Figure 4.31 (continued).

4.4 DAMAGE CHARACTERISTICS POST-STRENGTH

The damage state at 20% residual strength or an 80% drop below lateral strength offers an indication of the incipient failure mode of the wall. It is noted however, that not all of the cripple walls dropped 80% in strength, and those that did not will be noted in the 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 post-strength and residual strength characteristics were defined for the wall. In some instances, the monotonic push was not implemented if it was deemed that the post-strength response had already been adequately characterized.

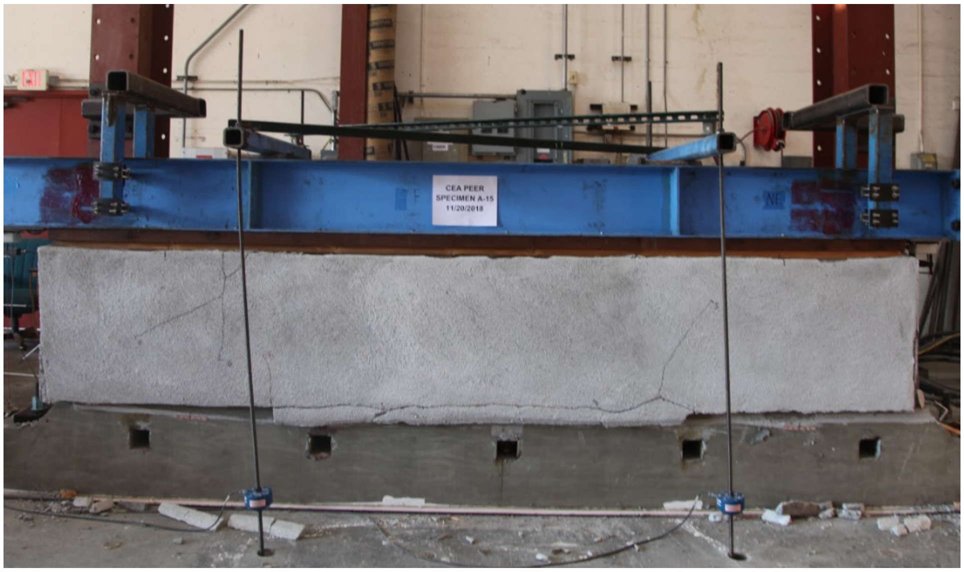
4.4.1 Specimen A-15 Post-Strength to Performance

Figure 4.32 shows the state of Specimen A-15 at the +13% global drift ratio unless otherwise noted. At this point, the capacity of the cripple wall had dropped by 70% from lateral strength. A cross-grain sill crack had propagated across the entire span of the sill plate. The crack ran through the location of all the anchor bolts, as shown in Figure 4.32(a) and (d). Due to this cracking, most of the imposed displacement was in the form of the sill plate displacing relative to the foundation, as shown by the cripple wall overhanging the side of the foundation in Figure 4.32(c). Increases in the drift amplitude were not expected to result in further drops of load because the strength was primarily attributed to the frictional resistance between the sill plate and foundation, which was not subject to change. Because of this, no monotonic push was initiated. The test finished after the end of the 13% drift ratio cycle group. Figure 4.33 shows photographs of the residual state of the wall at the end of the test. The last imposed drift ratio was -13% global drift ratio; in the residual state, -2.75 in. (-11.5% global drift ratio) remained in the cripple wall. Most of drift was from the offset of the cripple wall due to the displacement of the sill plate relative to the foundation. Along the exterior face of the specimen, some additional cracks had accrued upon reaching strength; see Figure 4.33(a). Throughout the interior, the studs and top plates showed little damage, but some cracks had formed in the sheathing boards; see Figure 4.33(b). At both corners, the stucco had detached from the sheathing and framing, but there were no large crack openings as exhibited by the other specimens tested; see Figure 4.34(c) and (d). This indicates that the stucco had not fully detached from the framing at the sill plate and bottom of the studs.



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

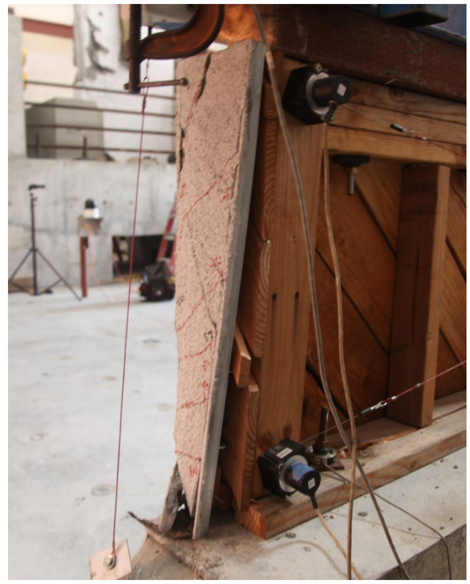
Figure 4.32 Specimen A-15 damage state at 70% post-strength reduction of lateral strength at +13% drift ratio @ Δ = +3.12 in. unless otherwise stated: (a) bottom of south-end interior of wall view; (b) bottom of south-end interior of wall view at -13% drift; (c) bottom of south-end exterior corner of wall view at -13% drift; and (d) bottom of north-end of wall view.



(a)

(b)

Figure 4.33 Specimen A-15 post-test photographs with lateral load = 0 kips at residual displacement = -2.75 in. @ -11.5% drift ratio after completing 13% drift ratio cycle group: (a) exterior elevation; (b) interior elevation; (c) south-end exterior corner of wall view; and (d) north-end interior corner of wall view.

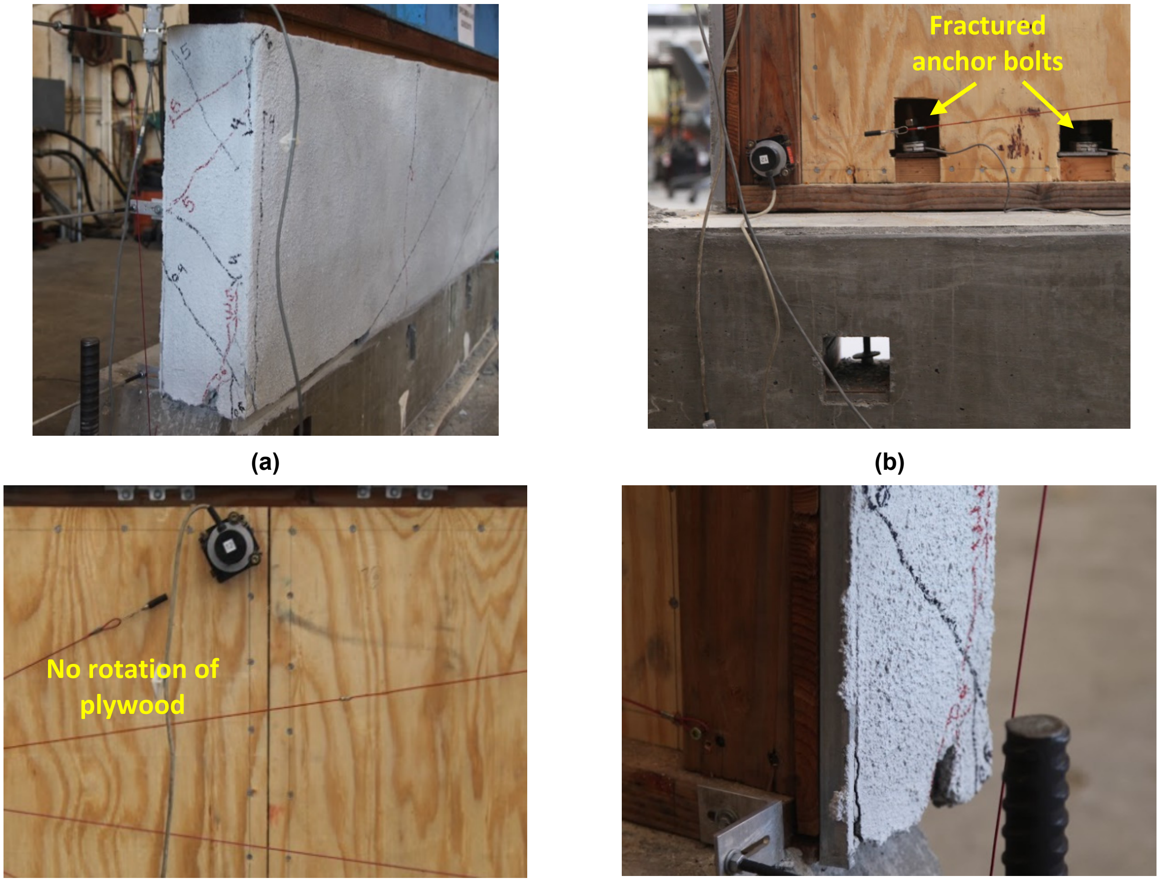


(c) (d)

Figure 4.33 (continued).

4.4.2 Specimen A-16 Post-Strength to Performance

Figure 4.34 shows the state of Specimen A-16 at the -9% global drift ratio. At this point, the capacity of the cripple wall had dropped by 80% from lateral strength. Fractures to all the anchor bolts had resulted in the drop of load, as seen in Figure 4.34(b). A cross-grain sill crack had also propagated across the entire span of the sill plate, which was similar to the existing counterpart cripple wall. Therefore, the displacement of the cripple wall was almost all due to the displacement of the sill plate relative to the foundation, as shown by the cripple wall overhanging the edge of the foundation; see Figure 4.34 (a) and (b). Along the interior, there was little damage to the plywood panels and no visible rotation to the panels; see Figure 4.34(c). The lack of damage to the plywood indicates that the retrofit would have been able to supply additional strength to the cripple wall had the anchor bolts and sill plate not been critically damaged. Figure 4.35 shows the residual state of the cripple wall at the end of the test. Once the 9% global drift ratio cycles had been completed, the cripple wall was monotonically pushed to +3.12 in. or +13% global drift ratio. The residual displacement after the push was +2.96 in. or +12.4% drift ratio. As with Specimen A-15, the majority of the resistance came from the frictional resistance between the sill plate and foundation. There was no increase in load when the monotonic push was performed. Some additional cracks in the stucco formed along the exterior face post-strength; see Figure 4.35(a). On the interior face, the plywood and blocking were mostly intact. Many of the nails had rotated to some degree, but there was no edge tear through, pull through, or withdrawal of any of the fasteners; see Figure 4.35 (b) and (d). The connection of the stucco to the sheathing and framing remained intact as well, as evidenced by the lack of crack openings in the stucco at the corners of the specimen; see Figure 4.35(c).



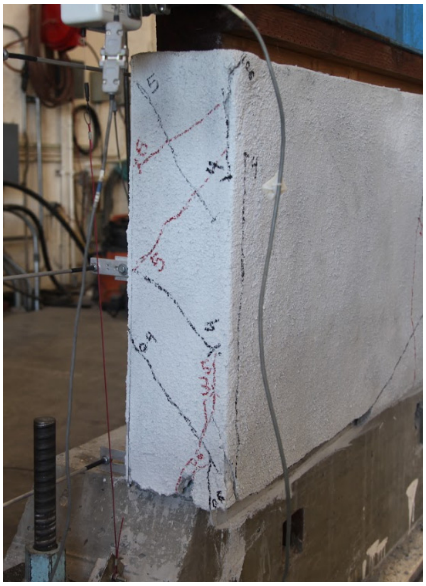
(a) (b) (c) (d)

Figure 4.34 Specimen A-16 damage state at 80% post-strength reduction of lateral strength at -9% drift ratio @ Δ = -2.16 in.: (a) south-end exterior corner of wall view; (b) bottom of north-end interior of wall view; (c) top interior of wall view (south and middle panels); and (d) bottom of south-end interior corner of wall view.

(a)

(b)

Figure 4.35 **Specimen A-16 post-test photographs with lateral load = 0 kips at residual displacement = +2.96 in. @ +12.4% drift ratio after monotonic push to +3.12 in. at +13% drift ratio: (a) exterior elevation; (b) interior elevation; (c) south-end exterior corner of wall view; and (d) south-end interior of wall view.**



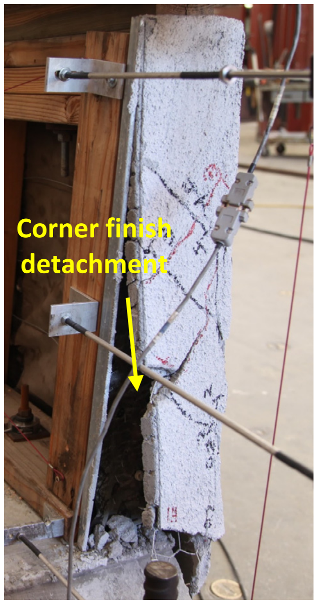
(c)

(d)

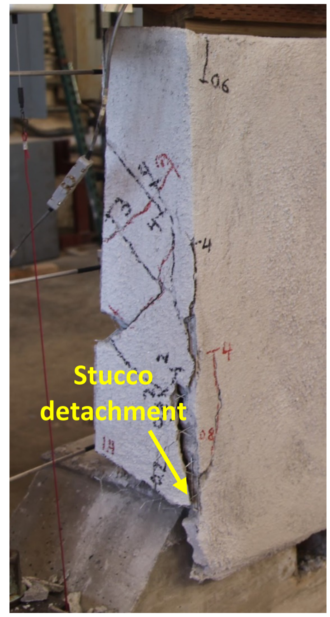
Figure 4.35 (continued).

4.4.3 Specimen A-17 Post-Strength to Performance

Figure 4.36 shows the state of Specimen A-17 at the +8% global drift ratio where an 80% drop in lateral strength occurred. At this point, 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 tops of the studs, indicated by the large crack openings in the stucco at the corners; see Figure 4.36(b). The stucco had detached from the framing at both ends, as shown in Figure 4.26(a) and (d). Once the stucco had lost most of its attachment, it was no longer able to provide a significant amount of lateral resistance. Figure 4.37 shows the residual state of the specimen after a monotonic push to +5.0 in. (+20.8% global drift ratio). The residual displacement was +4.76 in. (+19.8% global drift ratio). As shown in Figure 4.37 (a) and (c), a large crack opened in the stucco and propagated all the way to the uppermost top plate. The metal lath had completely ruptured over two-thirds of the height of the cripple wall. At this point, stucco only remained attached to the furring nails at the top plates. There was no visible damage to the framing of the cripple wall besides rotations of the studs; see Figure 4.37(b). The stucco had mostly detached from the framing at the corners as well.



(a)

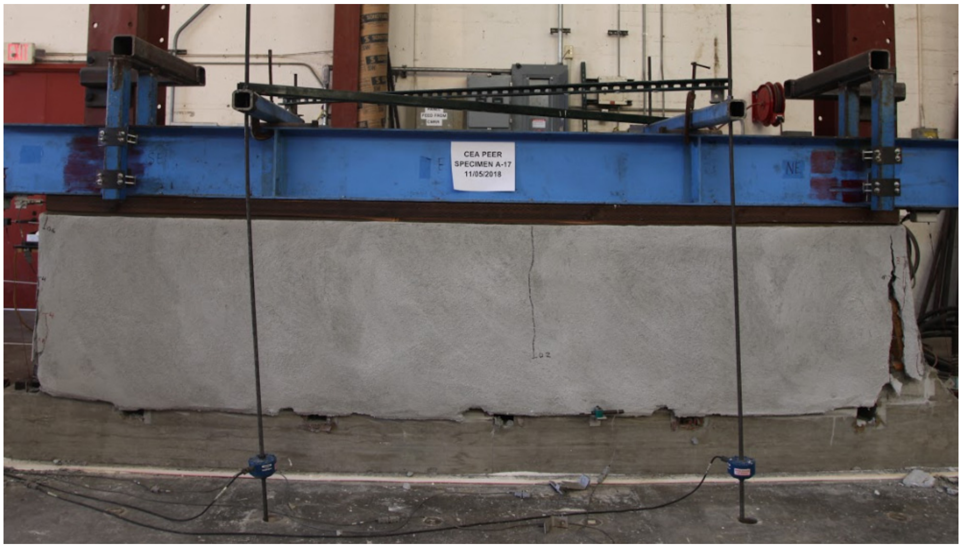


(b)

(c)

(d)

Figure 4.36 **Specimen A-17 damage state at 80% post-strength reduction of lateral strength at +8% drift ratio @ Δ = +1.92 in.: (a) south-end interior corner of wall view; (b) south-end exterior corner of wall view; (c) north-end interior of wall view; and (d) south-end interior of wall view.**



(a)

(b)

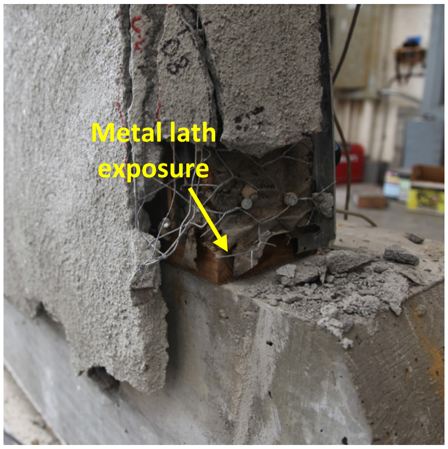
Figure 4.37 **Specimen A-17 post-test photographs with lateral load = 0 kips at residual displacement = +4.76 in. @ +19.8% drift ratio after monotonic push to +5.0 in. @ +20.8% drift ratio: (a) exterior elevation; (b) interior elevation; (c) north-end exterior of wall view; and (d) south-end interior corner of wall view.**

(c) (d)

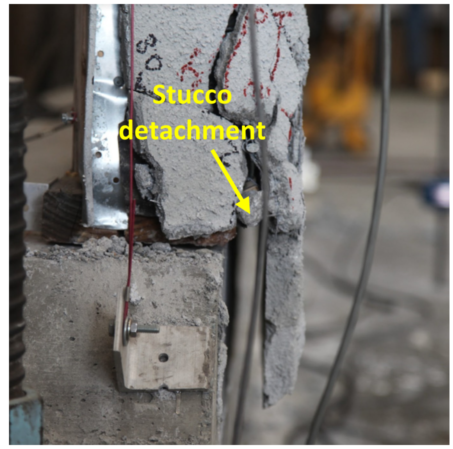
Figure 4.37 (continued).

4.4.4 Specimen A-18 Post-Strength to Performance

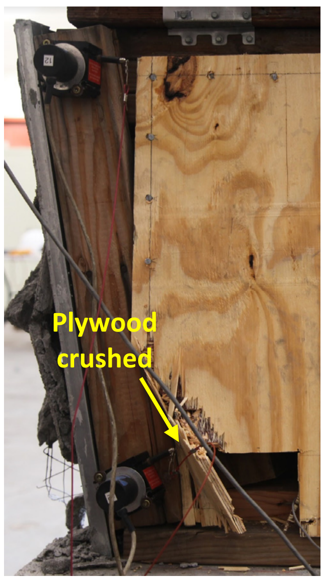
Figure 4.38 shows the state of Specimen A-18 at the +15% global drift ratio where an 80% drop in lateral strength occurred. As with existing Specimen A-17, the stucco finish had detached from most of the furring nails on the studs and remained only attached to the furring nails at the top plates and the tops of the studs, indicated by the large gap that formed between the stucco extension and the foundation; see Figure 4.36(a) and (b). The stucco had mostly detached from the framing at the corners as well. The plywood was heavily damaged along the interior. The nails attaching the plywood to the framing had withdrawn from the framing at many locations; see Figure 4.36(d). At other locations, the fasteners had torn through the edges of the panels or pulled through the panels and remained attached to the framing. Overall, the plywood panels maintained little attachment to the framing, which can be seen by the lack of panel rotation in Figure 4.38(e). The plywood panels had crushed against the flat studs at the ends; see Figure 4.38(c). Figure 4.39 shows the residual state of the specimen after a monotonic push to +5.0 in. (+20.8% global drift ratio). The residual displacement was +4.52 in. (+18.8% global drift ratio). Along the exterior face, no additional vertical cracks propagated post-strength, but the cracks at the edges had opened significantly; see Figure 4.39(a) and (c). Much of the metal lath had ruptured at these locations. Along the interior, each of the plywood panels only maintained connection to the framing at one edge; see Figure 4.39(b) and (d). The north and middle panel were bearing on each other during the monotonic push, causing the panels to tear and overlap as shown in Figure 4.38(b). Large cracks opened in the stucco at both corners. The blocking remained mostly intact.



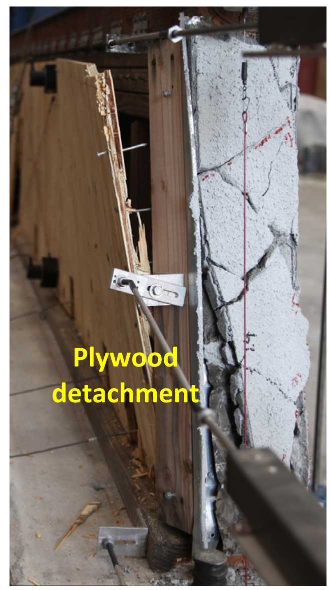
(a)



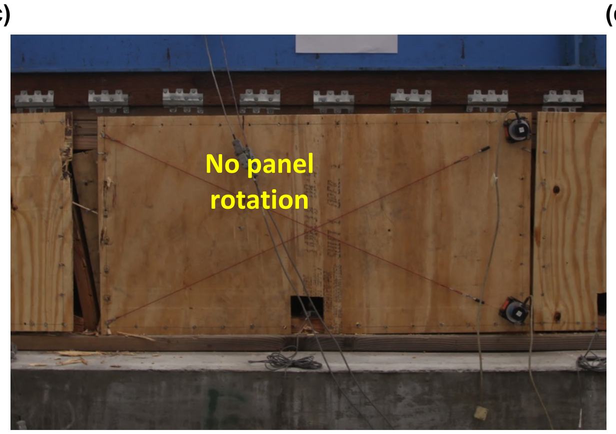
(b)



(c)

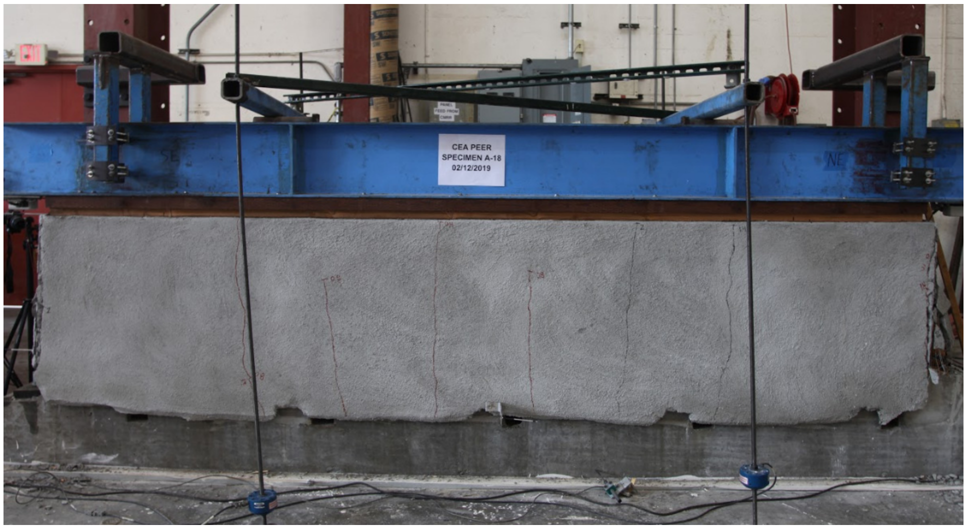


(d)



(e)

Figure 4.38 Specimen A-18 damage state at 80% post-strength reduction of lateral strength at +15% drift ratio @ Δ = +3.6 in.: (a) bottom of north-end exterior corner of wall view; (b) bottom of south-end corner of wall view; (c) north-end interior of wall view; (d) south-end interior corner of wall view; and (e) middle interior of wall view.



(a)

(b)

Figure 4.39 **Specimen A-18 post-test photographs with lateral load = 0 kips at residual displacement = +4.52 in. @ +18.8% drift ratio after monotonic push to +5.0 in. @ +20.8% drift ratio: (a) exterior elevation; (b) interior elevation; (c) north-end exterior corner of wall view; and (d) south-end interior corner of wall view.**

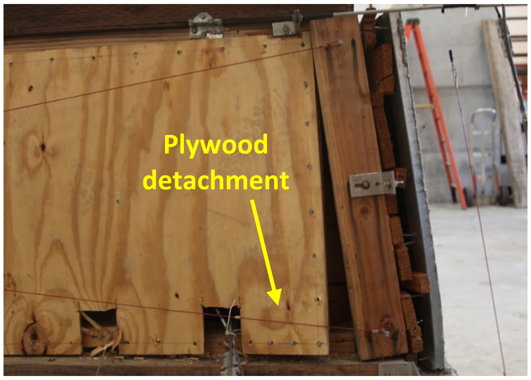
(c)

(d)

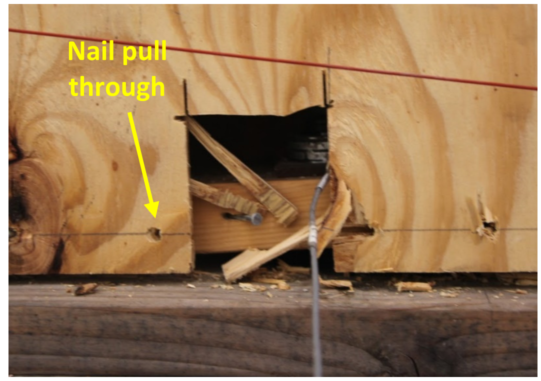
Figure 4.39 (continued).

4.4.5 Specimen A-19 Post-Strength to Performance

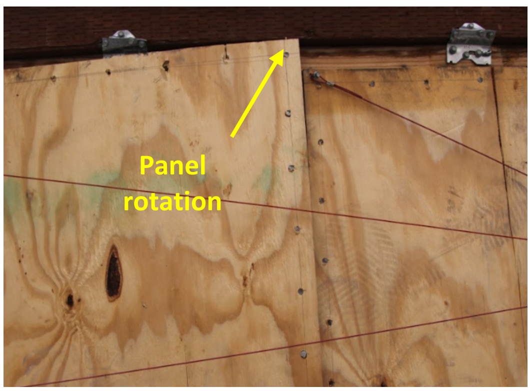
Figure 4.40 shows the state of Specimen A-19 at the -12% global drift ratio where an 80% drop in lateral strength occurred. The stucco finish had detached from most of the furring nails on the studs and remained only attached to the furring nails at the top plates and the tops of the studs, as was the case for all wet finished specimens. This is indicated by the large cracks in the stucco at the corners; see Figure 4.40(d). Along the interior, the plywood panels had rotated heavily and were detached from the framing at many locations; see Figure 4.40(a) and (c). Most of the nails at the bottom of panels had either torn through the edges of the panels of pulled through the plywood; see Figure 4.40(d). At the corners, most of the sheathing boards had split. Many of the sheathing boards also detached from the framing, while the stucco had fully detached from the framing, as seen in Figure 4.40(a). Figure 4.41 shows the residual state of the specimen after a monotonic push to +5.0 in. (+20.8% global drift ratio). The residual displacement was +4.26 in. (+17.8% global drift ratio). Along the exterior face, no additional vertical cracks propagated post-strength, but the cracks at the edges had opened significantly; see Figure 4.41(a) and (c). The metal lath at the north corner had ruptured from the bottom of the wall all the way to the bottom of the top plates. The only remaining attachment of the plywood panels was at the top of the cripple walls. The north panel had nearly completely detached; see Figure 4.41(b). In addition, the plywood panels had crushed against the flat end studs. As with retrofitted Specimen A-18, the blocking remained relatively intact.



(a)



(b)

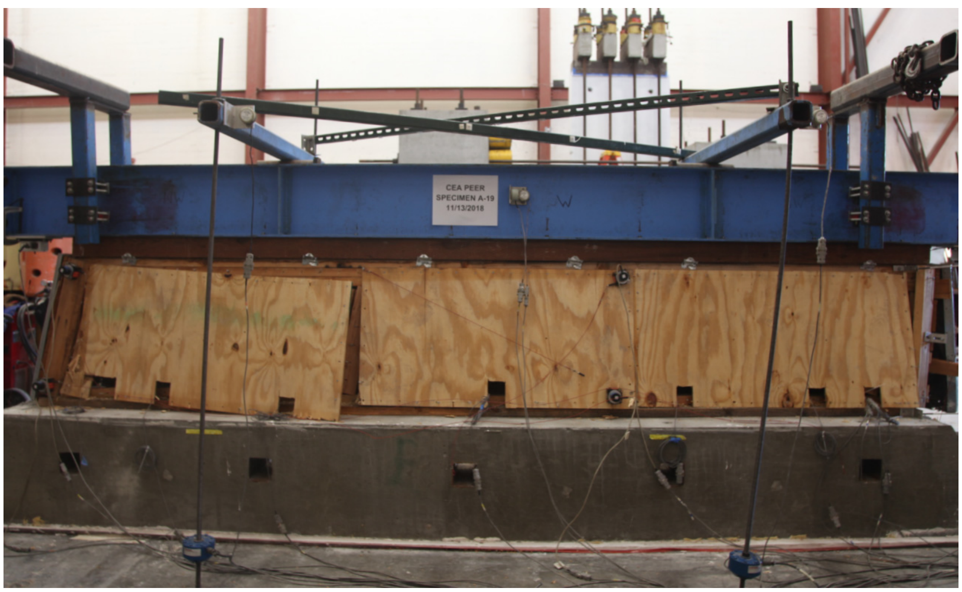


(c)

(d)

Figure 4.40 **Specimen A-19 damage state at 80% post-strength reduction of lateral strength at -12% drift ratio @ Δ = -2.88 in.: (a) south-end interior of wall view; (b) bottom interior of wall view (south pane); (c) top interior of wall view (north and middle panels); and (d) bottom of south-end corner of wall view.**

(a)



(b)

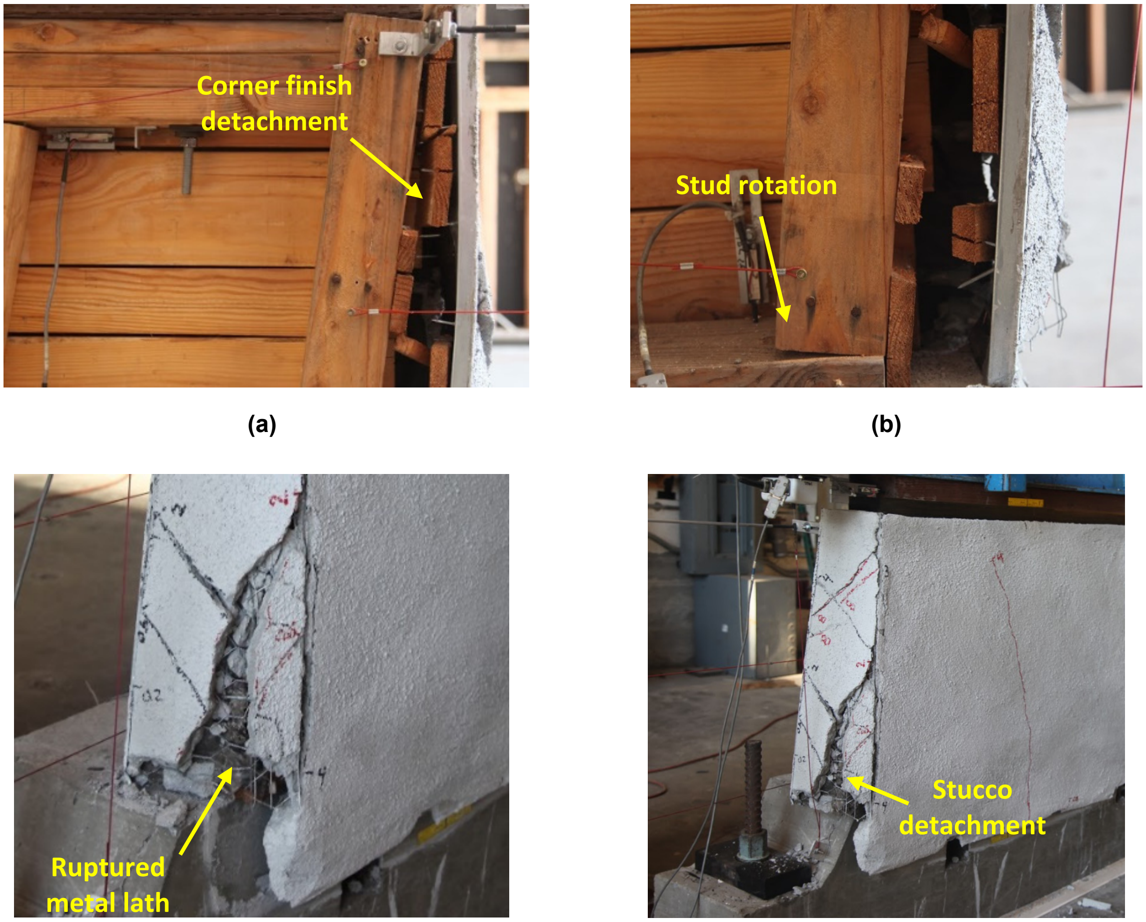
Figure 4.41 Specimen A-19 post-test photographs with lateral load = 0 kips at residual displacement = +4.26 in. @ +17.8% drift ratio after monotonic push to +5.0 in. @ +20.8% drift ratio: (a) exterior elevation; (b) interior elevation; (c) north-end exterior of wall view; and (d) north-end interior corner of wall view.

(c) (d)

Figure 4.41 (continued).

4.4.6 Specimen A-20 Post-Strength to Performance

Figure 4.42 shows the state of Specimen A-20 at the -14% global drift ratio where an 80% drop in lateral strength occurred. As shown in Figure 4.42(c) and (d), large cracks opened in the stucco, indicating that 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 tops of the studs. At the bottom of the corners, the metal lath had ruptured. Most of the sheathing boards at the corners had cracked and detached from the framing along with the stucco; see Figure 4.42(a) and (b). There was little damage to the sheathing boards that spanned across the face of the cripple wall. The loss of strength was primarily due to the detachment of the stucco from most of the cripple wall as the horizontal sheathing boards did not provide a large amount of lateral resistance relative to the contribution from the stucco. In Figure 4.43, the residual state of the specimen is shown after a monotonic push to +5.0 in. (+20.8% global drift ratio). The residual displacement was +4.81 in. (+20.0% global drift ratio). Along the exterior face, no additional vertical cracks propagated post-strength, but the cracks at the edges had opened significantly; see Figure 4.43(a) and (c). At this point the only remaining attachment of the stucco to the framing was at the top plates and at the corners where the stucco was nearly fully detached; see Figure 4.43(d). Both the framing and the sheathing boards exhibited little visible damage along the interior of the cripple walls; see Figure 4.43(b).



(a) (b)

(c) (d)

Figure 4.42 Specimen A-20 damage state at 80% post-strength lateral load at -14% drift ratio @ Δ = -3.36 in. unless otherwise noted: (a) top of south-end interior of wall view at +14% drift; (b) bottom of south-end interior of wall view at +14% drift; (c) bottom of south-end exterior corner of wall view; and (d) south-end exterior corner of wall view.

(a)

(b)

Figure 4.43 Specimen A-20 post-test photographs with lateral load = 0 kips at residual displacement = +4.81 in. @ +20.0% drift ratio after monotonic push to +5.0 in. @ +20.8% drift ratio: (a) exterior elevation; (b) interior elevation; (c) north-end exterior corner of wall view; and (d) south-end interior corner of wall view.

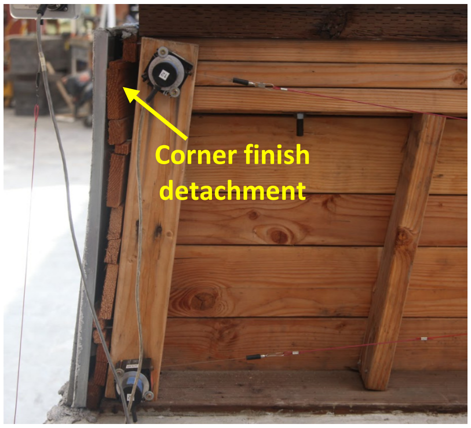
(c)

(d)

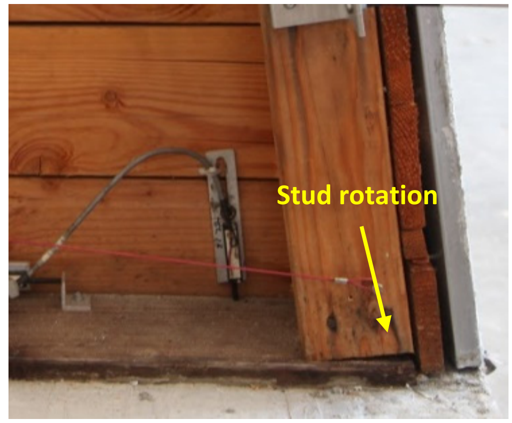
Figure 4.43 (continued).

4.4.7 Specimen A-21 Post-Strength to Performance

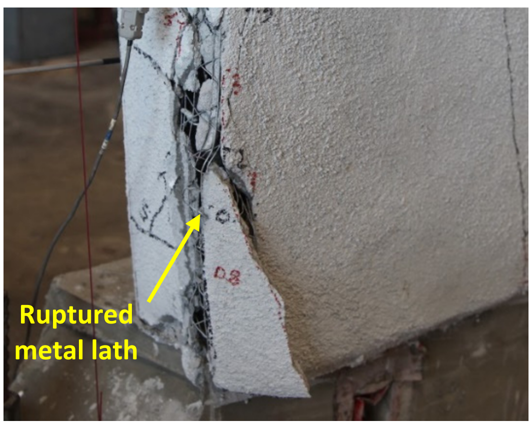
Figure 4.44 shows the state of Specimen A-21 at the +14% global drift ratio unless otherwise noted, where an 80% drop in lateral strength occurred. The damage characteristics are nearly the same as Specimen A-20, which had a typical anchorage condition instead of a wet set sill plate. In Figure 4.44 (c) and (d), large cracks opened in the stucco and propagated up the wall. The metal lath at the bottom of the wall had ruptured as well; see Figure 4.44(c) and (d). This indicates that 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 tops of the studs. Most of the sheathing boards at the corners had cracked and but remained partially attached to the framing even though the stucco had detached; see Figure 4.42(a) and (b). The sheathing boards that spanned across the face of the cripple wall experienced little damage. The gaps between the sheathing boards had closed considerably more when compared to Specimen A-20, which is attributed to the imposed displacement being carried only by the wall instead of displacements between the sill plate and the foundation. As with the previous stucco over horizontal sheathing finished cripple wall, the loss of strength was primarily due to the detachment of the stucco from most of the cripple wall as the horizontal sheathing boards did not provide a large amount of lateral resistance relative to the contribution from the stucco. Figure 4.45 shows the residual state of the specimen after a monotonic push to +5.0 in. (+20.8% global drift ratio). The residual displacement was +4.62 in. (+19.3% global drift ratio). Along the exterior face, the cracks at the edges had opened significantly; see Figure 4.45(a) and (c). The metal lath had ruptured over halfway up the specimen. The gaps between the sheathing boards had all closed, and the boards began to bear on one another, which can be seen in Figure 4.45(b) and (d). The bearing of the sheathing boards provided a significant increase in strength compared to the last displacement cycle.



(a)



(b)



(c)

(d)

Figure 4.44 Specimen A-21 damage state at 80% post-strength lateral load at +14% drift ratio @ Δ = +3.36 in. unless otherwise noted: (a) south-end interior of wall view; (b) bottom of south-end interior of wall view at -14% drift; (c) south-end exterior corner of wall view; and (d) north-end exterior corner of wall view.

(a)

(b)

Figure 4.45 Specimen A-21 post-test photographs with lateral load = 0 kips at residual displacement = +4.62 in. @ +19.3% drift ratio after monotonic push to +5.0 in. @ +20.8% drift ratio: (a) exterior elevation; (b) interior elevation; (c) north-end exterior corner of wall view; and (d) south-end interior of wall view.

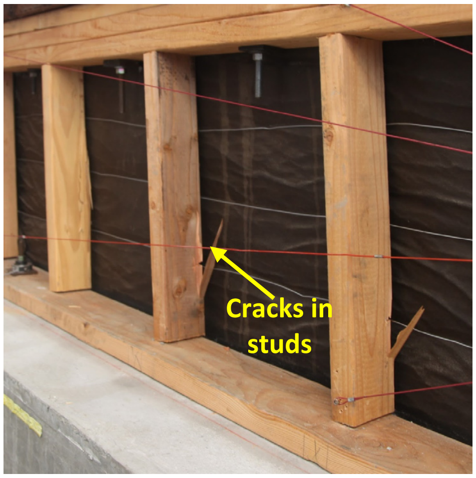
(c)

(d)

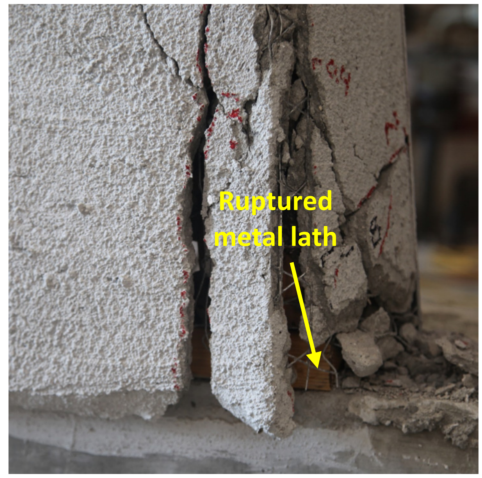
Figure 4.45 (continued).

4.4.8 Specimen A-22 Post-Strength to Performance

Figure 4.46 shows the state of Specimen A-22 at the -9% global drift ratio where an 80% drop in lateral strength occurred. The drop in strength occurred slightly later (+8% global drift versus -9% global drift) compared to Specimen A-17 (the existing cripple wall finished with stucco). The damage to both specimens was nearly the same. 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 tops of the studs. Large cracks in the stucco at the corners are shown in Figure 4.46(b) and (d). Some of the studs had cracked at locations where the furring nails had detached from the framing; see Figure 4.46(c). In Figure 4.47, the residual state of the specimen is shown after a monotonic push to +5.0 in. (+20.8% global drift ratio). The residual displacement was +4.87 in. (+20.3% global drift ratio), indicating that the stucco was providing almost no lateral resistance. Figure 4.47 (a) and (c) shows a large crack had opened in the stucco, propagating all the way to the bottom of the top plates. The metal lath had completely ruptured over two thirds of the height of the cripple wall. The cracking pattern indicates that the stucco only remained attached to the furring nails at the top plates. There was no further damage to the framing with only large rotations of the studs; see Figure 4.47(b). The stucco had mostly detached from the framing at the corners as well; see Figure 4.47(d).

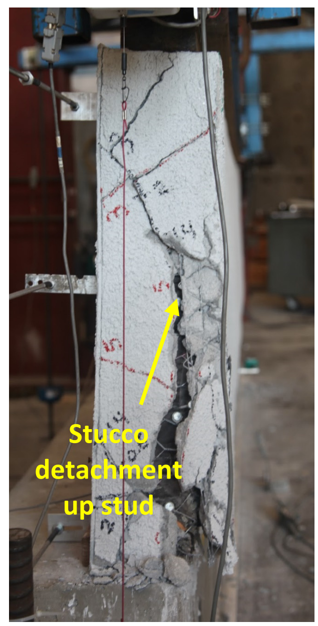


(a)



(b)

(c)



(d)

Figure 4.46 **Specimen A-22 damage state at 80% post-strength lateral load at -9% drift ratio @ Δ = -2.16 in. unless otherwise noted: (a) middle interior of wall view; (b) bottom of north-end exterior of wall view; (c) north-end interior of wall view at +9% drift; and (d) south-end corner of wall view.**

(a)

(b)

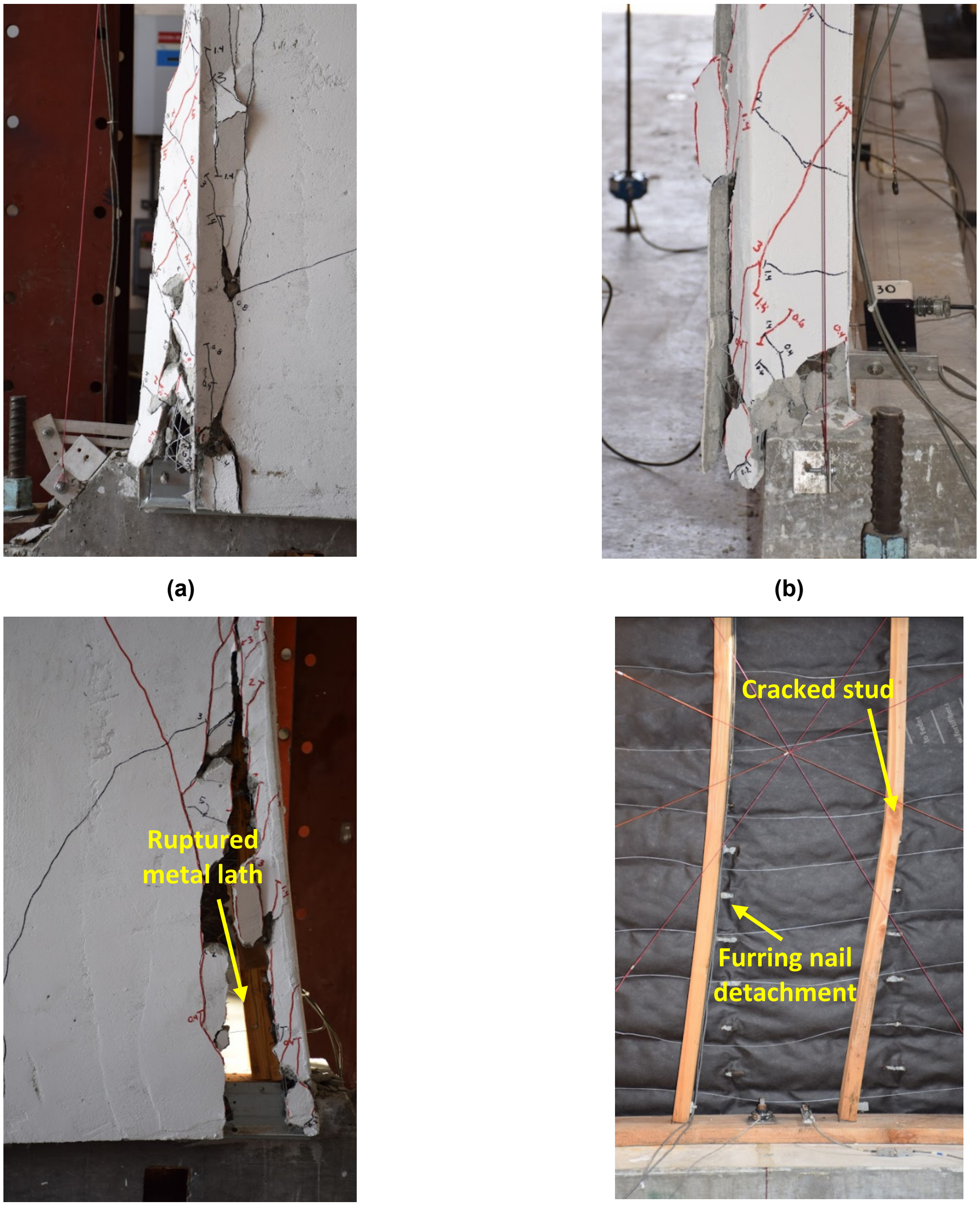
Figure 4.47 Specimen A-22 post-test photographs with lateral load = 0 kips at residual displacement = +4.87 in. @ +20.3% drift ratio after monotonic push to +5.0 in. @ +20.8% drift ratio: (a) exterior elevation; (b) interior elevation; (c) north-end exterior corner of wall view; and (d) south-end interior corner of wall view.

(c) (d)

Figure 4.47 (continued).

4.4.9 Specimen A-25 Post-Strength to Performance

Figure 4.48 shows Specimen A-25 at the -7% global drift ratio unless otherwise noted, where an 80% drop in lateral strength occurred. The drop in strength occurred slightly earlier than for Specimens A-17 and A-22 (the existing 2-ft-tall cripple walls finished with stucco). 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. Large cracks in the stucco at the corners are shown in Figure 4.48(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, as shown in Figure 4.48(d). In Figure 4.49, the residual state of the specimen is shown after a monotonic push to +6.5 in. (+9.1% global drift ratio). The residual displacement was +2.92 in. (+4.1% global drift ratio). The residual deformation indicates that the stucco provided some lateral resistance, which was maintained evidenced from the attachment to the upper third of the cripple wall; see Figure 4.49(c). In Figure 4.49 (a) and (c), large cracks in the stucco had propagated up three-quarters of the specimen. No additional cracks had formed along the face of the specimen post-strength; see Figure 4.49(a). Increased cracking and opening of cracks were found at both corners; see Figure 4.49 (c) and (d). There was no further damage to the framing, only large rotations of the studs; see Figure 4.47(b). The studs were no longer bent due to the drop in strength.



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

Figure 4.48 Specimen A-25 damage state at 80% post-strength lateral load at -7% drift ratio @ Δ = -6.48 in. unless otherwise noted: (a) bottom of south-end exterior corner of wall view; (b) bottom of north-end corner of wall view; (c) bottom of north-end exterior of wall view; and (d) middle interior of wall view at +7% drift.

(a)

(b)

Figure 4.49 **Specimen A-25 post-test photographs with lateral load = 0 kips at residual displacement = +2.92 in. @ +4.1% drift ratio after monotonic push to 6.50 in. @ +9.1% drift ratio: (a) exterior elevation; (b) interior elevation; (c) south-end exterior corner of wall view; and (d) north-end interior corner of wall view.**

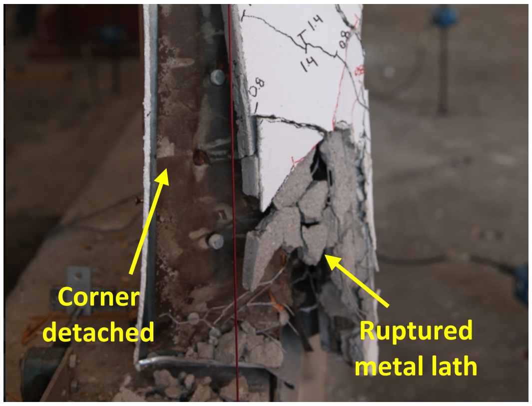
(c)

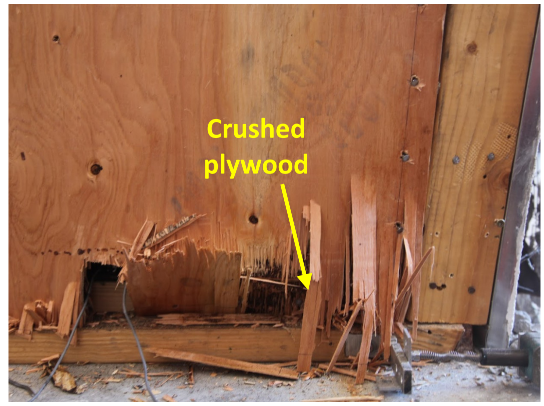
(d)

Figure 4.49 (continued).

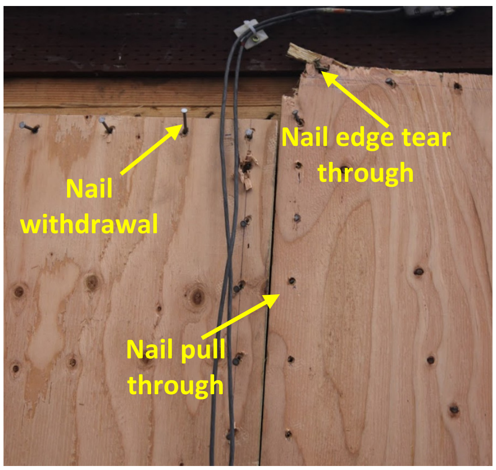
4.4.10 Specimen A-26 Post-Strength to Performance

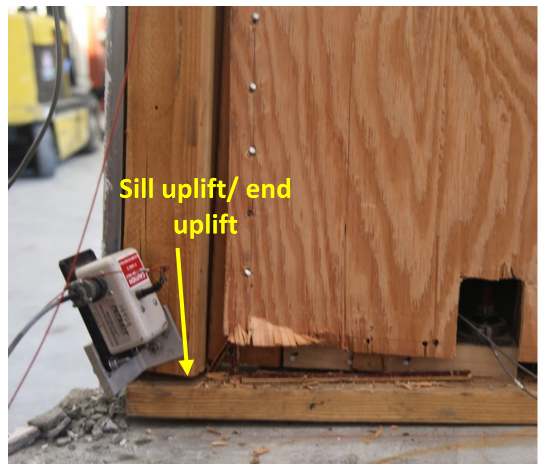
Figure 4.50 shows Specimen A-26 at the +8% global drift ratio where an 80% drop in lateral strength occurred. This drop in strength occurred much earlier than in Specimen A-18, the retrofitted 2-ft-tall cripple wall finished with stucco. The stucco finish had detached from most of the furring nails on the studs and remained only attached to the furring nails at the top plates and the top third of the studs (the same response as 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 4.50(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 4.50(b). At the bottom of the panels, the fasteners either pulled through the panels or tore through the edges of the panels [Figure 4.50(d)]. As shown in Figure 4.50(c). there was assortment of nails withdrawing from the framing, pulling through the plywood, or tearing through the plywood edges at the top of the walls. Figure 4.51 shows the residual state of the specimen is after completing the 9% global drift ratio cycle: the residual displacement was -4.75 in. (-6.6% global drift ratio). A monotonic push was not implemented as the residual response of the specimen was deemed to already have been well characterized. As shown in Figure 4.51 (a) and (c), large crack openings in the stucco propagating up two-thirds of the specimen. No additional cracks formed along the face of the specimen post-strength; see Figure 4.51(a). The stucco had detached from the bottom two-thirds of the corners and was out-of-plane; see Figure 4.51(c). Along the interior, the panels had lost most of their connection to the framing and were heavily rotated; see Figure 4.51(b).





(a) (b)





(c) (d)

Figure 4.50 **Specimen A-26 damage state at 80% post-strength lateral load at +8% drift ratio @ Δ = +5.76 in.: (a) bottom of south-end corner of wall view; (b) bottom of south-end interior of wall view; (c) top of middle interior of wall view (south and middle panels); and (d) bottom of north-end interior of wall view.**

(a)

(b)

Figure 4.51 **Specimen A-26 post-test photographs with lateral load = 0 kips at residual displacement -4.75 in. @ -6.6% drift ratio after completing the 9% drift ratio cycle group: (a) exterior elevation; (b) interior elevation; (c) south-end corner of wall view; and (d) south-end interior of wall view.**

(c)

(d)

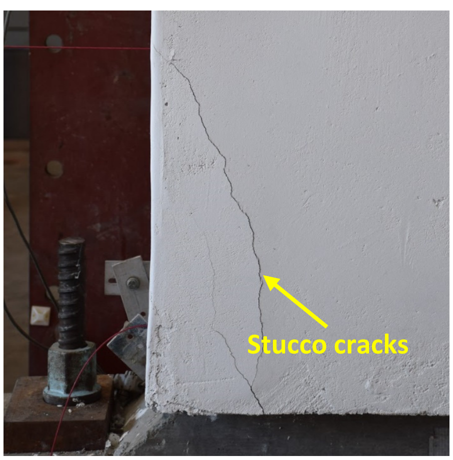
Figure 4.51 (continued).

4.4.11 Specimen A-27 Post-Strength to Performance

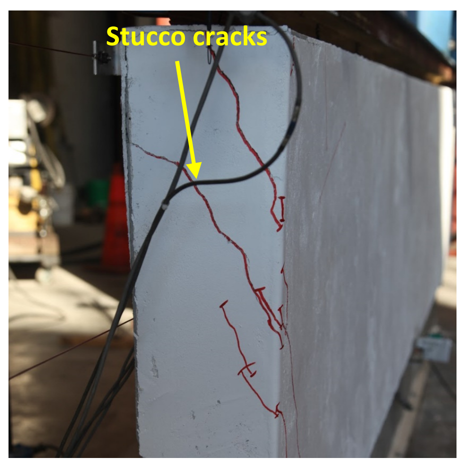
Figure 4.52 shows the residual state of Specimen A-27 after a monotonic push to +5.0 in. (+20.8% global drift ratio). Recall that the loading protocol for this specimen was monotonic, not cyclic. The cripple wall reached strength at the 6% global drift ratio and 5.4% relative drift ratio. Along the exterior face, a large piece of stucco at the north end had almost completely detached from the sheathing/framing; see Figure 4.52(a) and (g). There were additional vertical cracks as well, but none of them as significant; see Figure 4.52(c). The stucco had moved out-of-plane at the bottom of the wall, producing a gap between the stucco and the foundation; see Figure 4.52(e), (f), and (h). Cracking also appeared at the bottom of both corners, as seen in Figure 4.52(d) and (g). The framing and sheathing remained relatively intact along the interior of the specimen; see Figure 4.52(b). Most of the gaps between the sheathing boards had closed up, but there was no increase in strength at the end of the monotonic push as was seen with the cripple wall with stucco over horizontal sheathing exterior finish and a wet set sill plate. This indicates that the sheathing boards had not yet begun to bear on each other in a manner sufficient to provide increased lateral resistance. At both corners, many of the sheathing boards had cracked and detached from the framing along with the stucco; see Figure 4.52(i) and (j). The loss of strength was attributed to the detachment of the stucco from the sheathing and framing along the sill plate and studs. Once this occurred, the sheathing and framing were the only materials left to provide lateral resistance.

(a)

(b)

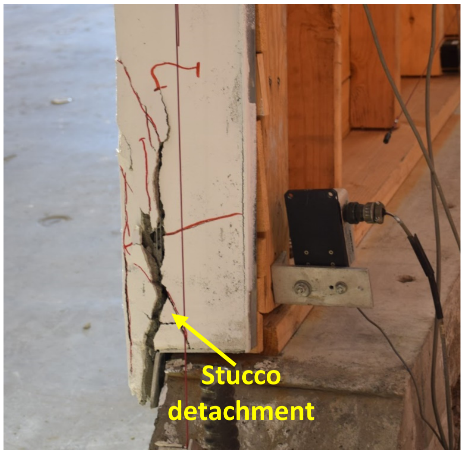


(c)

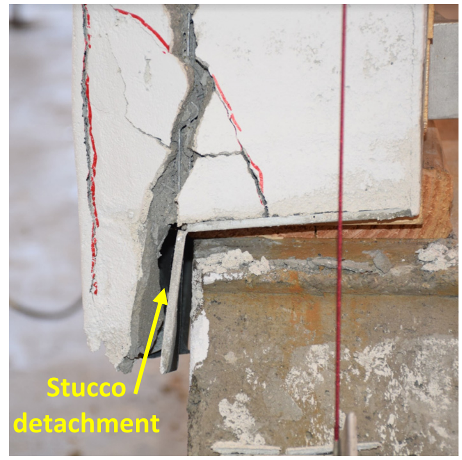


(d)

Figure 4.52 **Specimen A-27 post-test photographs with lateral load = 0 kips at residual displacement +4.55 in. @ 19.0% drift ratio after monotonic push to +4.76 in. @ +20% drift ratio: (a) exterior elevation; (b) interior elevation; (c) bottom of south-end exterior of wall view; (d) top of north-end exterior corner of wall view; (e) bottom of north-end interior corner of wall view; (f) bottom of north-end corner of wall view; (g) north-end exterior corner of wall view; (h) bottom of south-end corner of wall view; (i) north-end interior of wall view; and (j) south-end interior of wall view.**



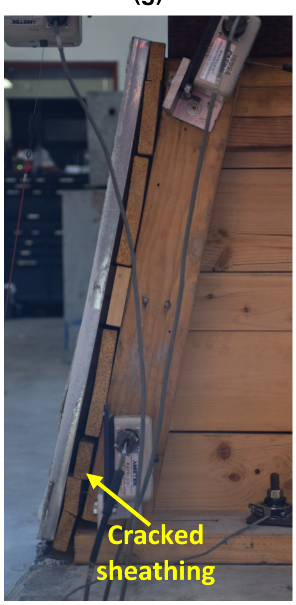
(e)



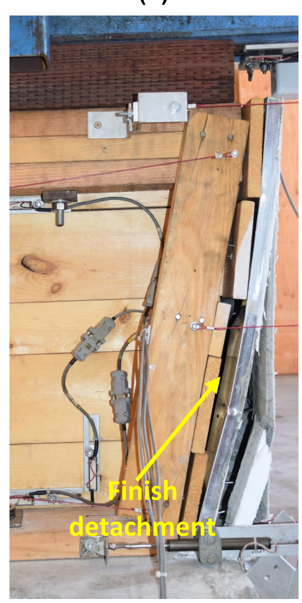
(f)

(g)

(h)



(i)



(j)

Figure 4.52 (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 cripple walls and inadequate sill bolting are 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 results from an experimental investigation to study the seismic performance of retrofitted and existing cripple walls with sill anchorage, with particular focus on wet (stucco) finished specimens. Paralleled by a large-component test program conducted at UC Berkeley [Cobeen et al. 2020], the present report involves a portion of a multi-phased small-component test suite conducted at UC San Diego. The small-component test program examined the following parameters: cripple wall height, finish style, gravity load, boundary conditions, anchorage, and deterioration. This report specifically addresses the third and half of the fourth phases of testing, which consisted of eleven specimens, all finished with wet (stucco) materials. In addition to varying the type of wet finish materials, parameters examined in this report included the height and effectiveness of the *FEMA P-1100* prescriptive retrofit guidelines. The exterior finishes used were stucco over framing, stucco over horizontal lumber sheathing, and stucco over diagonal lumber sheathing. The cripple wall studied were 2 ft and 6 ft high. The anchorage and boundary conditions on the top and corners of the cripple walls, cripple wall length, and applied vertical load were all held constant for each specimen. Two variations in the boundary condition for the bottom of the specimens were also considered. Finally, the same loading protocol was used for all tests discussed herein, with the exception of one specimen, which was subjected to a monotonic push. In what follows, conclusions specific to the parameters varied within the present report are summarized.

5.1 GENERAL OBSERVATIONS

The most notable general observations are as follows:

- The hysteresis of all specimens was generally stable with no abrupt brittle failure. As anticipated, the strength and stiffness of the unretrofitted (existing) specimens was much smaller than like specimens after retrofit; and

- For all existing specimens, loss of strength occurred when the stucco detached from the furring nails at the sill plate and bottom of the studs. The only exception to this was for the stucco over diagonal sheathing specimens, which lost strength due to a cross-grain crack in the sill plate.

5.2 IMPACT OF EXTERIOR FINISH[1]

5.2.1 Stucco Over Framing

- Stucco over framing was the weakest of the wet exterior finishes tested. Comparing the existing 2-ft-tall specimens, the stucco over framing finished cripple wall had around 55% of the lateral load capacity of the stucco over diagonal sheathing finished cripple wall, and around 95% of the capacity of the stucco over horizontal sheathing finished cripple wall;
- Stucco over framing had the lowest drift capacity and lowest drift at strength of any exterior finish. The average global drift ratio at strength for the existing 2-ft-tall specimens was 2.3% and the average relative drift ratio was 1.3%. For the existing 6-ft-tall specimen, these values were 1.4% and 1.1%, respectively. The existing 2-ft-tall specimens reached 40% residual strength by 4.6% relative drift, on average, while the existing 6-ft-tall specimen reached 40% residual strength by 5.0% relative drift;
- Stucco over framing was the stiffest of any wet exterior finish tested. The secant stiffness, defined at the secant stiffness associated with the relative drift at 80% pre-strength, was 150% larger for the existing 2-ft-tall specimens compared to the stucco over horizontal sheathing, and over 10% greater compared to specimens with stucco over diagonal sheathing; and
- The response was nearly symmetric in the push and pull loading directions for all stucco over framing finished specimens.

5.2.2 Stucco Over Horizontal Sheathing

- Stucco over horizontal sheathing was the second strongest exterior finish tested; worth noting is that the measured lateral strengths were close to the stucco over framing finish. For existing 2-ft-tall cripple walls with the same boundary and anchorage conditions, the stucco over horizontal sheathing provided only a 5% increase in lateral strength compared with the stucco over framing specimen;
- Stucco over horizontal sheathing had the largest drift capacity of any of the finish materials tested while the drift at strength was nearly equal to that of the stucco over diagonal sheathing finish. On average for the existing 2-ft-tall specimens, the global drift ratio at strength was 2.8% (2.5% relative drift ratio).

[1] Note that concluding remarks herein offer insight into the relative differences in strength and drift of various finished cripple walls to allow for concise conclusions, actual values (in plf) are reported within the body of the report

The existing 2-ft-tall specimens reached 40% residual strength by 8.7% relative drift on average for both directions of loading;

- Stucco over horizontal sheathing was the most flexible exterior finish tested. For existing 2-ft-tall specimens, the initial stiffness was 55% of the stucco over diagonal sheathing finish and 40% of the initial stiffness of the stucco over framing finish; and
- The response was nearly symmetric in the push and pull loading directions for all stucco over horizontal sheathing finished specimens.

5.2.3 Stucco Over Diagonal Sheathing

- Stucco over diagonal sheathing was the strongest exterior finish amongst the unretrofitted specimens tested. The average strength in both directions of loading was 75% greater than stucco over horizontal sheathing finish and 85% greater than the stucco over framing finish;
- The global drift ratio at strength was the largest of any of the finishes, with 4% global drift in the push loading direction and 5% global drift in the pull loading direction. The relative drift ratio at strength was the nearly the same as the stucco over horizontal sheathing finish, with an average relative drift ratio at strength of 2.3% for the stucco over diagonal sheathing finish and 2.4% for the stucco over horizontal sheathing specimen;
- The stucco over diagonal sheathing finish was the only finish 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 specimen 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. When the specimen was pulled on, the gaps between the sheathing boards close, the sheathing boards bear on each other and act in unison, similar to a wood structural panel; and
- Stucco over diagonal sheathing cripple walls experienced the most uplift at the wall ends of any of the finishes and the only existing 2-ft-tall specimen to show appreciable uplift. The largest uplift occurred at the North (pull) end during push loading due to the orientation of the sheathing boards.

5.3 IMPACT OF CRIPPLE WALL HEIGHT

- Taller cripple walls experience more uplift at their wall ends and more flexure than their smaller counterparts, which were dominated by a shear response. Existing specimens finished with stucco over framing specimens did not have the capacity to initiate any uplift, while the peak uplift for the 6-ft-tall specimen was between 0.1 and 0.2 in. In addition, there was a 60% reduction in initial stiffness for the existing 6-ft-tall specimen compared with the existing 2-ft-tall specimens;

- The strength was almost 20% larger for the taller stucco over framing finished specimen, which can be attributed to the increased number of furring nails fastening the stucco to the framing. For both the 2-ft- and 6-ft-tall specimens, the retrofitted specimens, the strength was nominally the same; and
- For the retrofitted cripple walls with stucco over framing exterior finish, the displacement at strength increased for the 6-ft-tall walls while the drift ratio at strength decreased. This is due to the drift ratio equating to three times as much displacement for the 6-ft-tall specimens compared to the 2-ft-tall specimens. The increased imposed displacement for 6-ft-tall walls caused the plywood to detach at a lower drift amplitude compared to the 2-ft-tall cripple wall. For the existing specimens, however, the drift capacity was similar regardless of height, while strength was attained at slightly lower drift amplitudes for the taller specimens: 1.1% relative drift ratio versus 1.3% relative drift ratio)

5.4 RESPONSE OF SPECIMENS RETROFIT ACCORDING TO *FEMA P-1100*

- All specimens retrofit with the *FEMA P-1100* guidelines observed increased strength, stiffness, and energy dissipation. In addition, the retrofit increased the drift capacity for all cripple walls, with the exception of those finished with stucco over diagonal sheathing, where the drift capacities amongst retrofit and existing specimens were nominally the same;
- The lowest increase in strength occurred with the stucco over diagonal sheathing cripple walls, with an average strength increase of 115%. Extrapolation of the strength of the stucco over diagonal sheathing finished specimens is difficult as these specimens suffered premature fracture of their anchor bolts due to cross-grain bending-induced cracks in the sill plate. The largest increase in strength occurred with stucco over horizontal sheathing specimens, where a 260% increase in lateral strength was observed. For the stucco over framing specimens, the strength increase was 225% for the 2-ft-tall specimens, and 180% for the 6-ft-tall specimens;
- The lowest increase in secant 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 30% and almost 60% for the 6-ft-tall specimens. The increase in secant stiffness was similar for both the stucco over horizontal sheathing and stucco over diagonal sheathing specimens, with almost a 125% increase for the stucco over horizontal sheathing finish and almost a 110% increase for the stucco over diagonal sheathing finish;
- The drift capacity increased the most for the retrofitted stucco over framing finished specimens. For the 2-ft-tall cripple walls, the drift at strength increased from 1.3% relative drift ratio to 4.8% relative drift ratio, and the relative drift ratio at 40% residual 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% residual strength increased from 5.0% to 7.1%. The stucco over horizontal sheathing specimens also experienced a dramatic increase in drift capacity, with the relative drift at strength increasing from 2.4% to 5.3%, and the relative drift ratio at 40% residual strength increased from 7.6% to 9.6%. The drift capacity for the stucco over diagonal sheathing cripple walls remained unchanged;

- An increase in cumulative energy dissipation was fairly consistent for the stucco over framing and stucco over horizontal sheathing specimens when retrofit. For stucco over horizontal sheathing finishes, there was an 8-fold increase in cumulative energy dissipated by the end of the test. The cumulative energy dissipated by the end of the test for the 2-ft-tall cripple wall with stucco over framing finish was increased around 7 times and increased around 8.5 times for the 6-ft-tall specimens; and
- Overall, loss of lateral strength occurred when the plywood panel detached from the framing. This occurred by either the nails tearing through the edges of the panels, the nails pulling through the panels, the nails pulling out of the framing, or the nails pulling the blocking off of the sill plate. For all specimens, the stucco had lost attachment to the sill plate and the bottom of the studs before reaching strength.

5.5 ANCHORAGE CONDITION

- With the presence of oversized anchor bolt holes, sliding of the sill plate relative to the concrete foundation occurred for the lower capacity specimens until anchor bolt bearing of the anchor bolt on the sill plate occurred. As such significant portions of the imposed drift were taken up by sliding of the sill plate on the concrete foundation, so much so that it became important to compare the global lateral response, which included the sill displacement, with the relative lateral response, which omitted the sill displacement. It is worth noting, however that the smooth trowel finished footings may divert from finished concrete footings of this vintage, thus offering reduced contribution to sliding;
- There was a 7% increase in strength for the cripple wall with a wet set sill plate over that with a traditional sill plate with anchor bolts. The wet set sill plate did not displace nor damage the surrounding concrete during loading; and
- The cumulative energy dissipated was nearly identical for the global response of the two cripple walls. For the relative response, the cumulative energy dissipated was around 30% larger for the wet set sill specimen.

5.6 BOTTOM BOUNDARY CONDITION

- Bottom boundary condition “d” entailed extending the stucco 8 in. down the face of the footing, creating a bond between the stucco finish and the face of the foundation. The bond between the stucco and the foundation proved to be fragile and partially detached during transportation of the specimens into the testing apparatus. It is likely due to this partial detachment that bottom boundary condition "d" behavior was nearly identical to bottom boundary condition "c" in all tests. It may be speculated that, given the vintage of the home of interest in these studies, such degradation at the interface between the cripple wall finish and exterior hard or softscape is plausible.

5.7 DAMAGE CHARACTERISTICS

- Significant cracking propagated vertically and diagonally at the corners (end of walls) even at low drift amplitudes (0.2%–1.4% drift amplitude). In addition, when corners were detailed with additional finish, vertical cracks also appeared on the exterior stucco face at the same low drift amplitudes. The extent of cracking and crack widths increased as the imposed drift increased. At large drift amplitudes, crushing and spalling of the stucco was observed in particular at the interface with the concrete foundation and again at the wall ends;
- Following attainment of full wall strength, 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);
- At very large drift amplitudes, some of the gaps between sheathing boards closed up, and individual sheathing boards began to bear upon each other. At this point, the sheathing boards bore on each other, resisting the lateral displacement of the cripple wall and causing a significant retention of the lateral strength of the cripple wall up to large drift amplitudes. This phenomenon was never fully realized for diagonal sheathing boards as the loss of strength capacity was associated with anchor bolt fractures and/or cross-grain sill plate cracks;
- Stucco over diagonal sheathing specimens tended to develop cross-grain bending sufficient enough to crack the sill plate due to the uplift of the diagonal specimen. Since the sheathing was only attached to the exterior edge of the sill plate, large uplift forces were transferred into one side of the sill plate while the other side—restrained by the anchor bolts—bore on the concrete footing;
- The stucco finish provided the majority of the stiffness and lateral strength of the cripple walls in all unretrofitted cases. Following attainment of the lateral capacity of the wall, the strength of the cripple wall decreased mostly due to the detachment of the stucco from the furring nails but also from the detachment of the furring nails from the sheathing and framing members. As drift amplitudes increased, the stucco finish was pushed out laterally at the base of the cripple wall, away from the sheathing and framing members as the furring nails detached. In many cases, at larger drift amplitudes the stucco finish retained its connection to only the top plates, providing very little lateral strength to the wall specimen. For taller specimens, the stucco remained attached to the top third of the stud height; and

- Failure of the retrofitted cripple wall was primarily attributed to 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 as added blocking split at large displacements. Some tearing of the nails through the plywood panels (edge tear-out) was also observed at the corners.

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Appendix A Material Properties

Appendix A includes three sections: lumber moisture content readings (A.1), stucco compressive strengths (A.2), and loading protocols (A.3). Discussion of these sections is provided in Chapter 3.

A.1 LUMBER MOISTURE CONTENT

The moisture content of the lumber for all cripple walls was measured and recorded using an MD912 digital moisture meter, a pin meter with a resolution of 0.5% and accuracy of +/- 0.5%. A picture of the moisture content reader is shown in Figure A.1. Understanding the moisture content of wood is important as drier wood has higher strength properties compared to fresh or moist wood. For all cripple walls, the moisture content ranged from 4–12% immediately prior to testing. The moisture content was considerably higher when the lumber was first purchased but dried out significantly before testing, especially after the application of the stucco finish. The moisture content was read on five various places on a piece of lumber—top, bottom, middle, and sides—and then repeated on four additional pieces of the same type of lumber. Table A.1 for Phase 3 specimens and Table A.2 for Phase 4 specimens lists the results, along with the date of recording and averages for each type of lumber.

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Figure A.1 MD912 digital moisture content reader in use.

Table A.1 Moisture content readings of Phase 3 lumber used in construction.

Construction Phase 3							
Lumber section	Moisture content Rreadings (%)					Average (%)	Date
2×6 #2 Douglas Fir	12.7	14.3	14	11.5	9.7	12.44	9/9/2018
2×4 #2 Douglas Fir	15.3	14.3	16.1	12.3	11.8	13.96	9/9/2018
2×6 construction grade Redwood	14.3	14.1	12.6	15.3	12.9	13.84	9/9/2018
1×6 construction Douglas Fir	10.2	9.8	11.7	11.3	13.2	11.24	9/9/2018

Test 15 – Specimen A-20							
Lumber section	Moisture content Rreadings (%)					Average (%)	Date
2×6 #2 Douglas Fir	11.2	10.3	11.1	10.2	9.4	10.44	10/22/2018
2×4 #2 Douglas Fir	9.8	8.7	10.2	11.3	9.7	9.94	10/22/2018
1×6 construction Douglas Fir	13.2	11.4	11.2	12.1	10.6	11.70	10/22/2018

Test 16 – Specimen A-22							
Lumber section	Moisture content Rreadings (%)					Average (%)	Date
2×6 #2 Douglas Fir	13.5	11.5	11.9	11.1	13.5	13.50	10/26/2018
2×4 #2 Douglas Fir	11.6	10.4	10.9	11.4	11.2	11.10	10/26/2018

Test 17 – Specimen A-21							
Lumber section	Moisture content Rreadings (%)					Average (%)	Date
2×6 construction grade Redwood	6.7	5.8	6.9	4.3	5.5	5.84	10/31/2018
2×4 #2 Douglas Fir	8.6	8.4	9.7	9.9	9.5	9.22	10/31/2018
1×6 construction Douglas Fir	8.7	10.2	9.5	9.6	10.3	9.66	10/31/2018

Test 18 – Specimen A-17							
Lumber section	Moisture content Rreadings (%)					Average (%)	Date
2×6 #2 Douglas Fir	9.6	12.3	10.4	10.8	11.1	9.60	11/5/2017
2×4 #2 Douglas Fir	9.6	10.4	9.9	11.2	10.4	10.30	11/5/2017

Test 19 – Specimen A-19							
Lumber Section	**Moisture content readings (%)**					**Average (%)**	**Date**
2×6 #2 Douglas Fir	10.1	11.1	9.5	9.4	10.6	10.14	11/13/2018
2×4 #2 Douglas Fir	9.6	9.5	10.2	10	8.7	9.60	11/13/2018
1×6 construction Douglas Fir	8.6	7.9	9.6	9.5	8.9	8.90	11/13/2018

Test 20 – Specimen A-15							
Lumber section	**Moisture content readings (%)**					**Average (%)**	**Date**
2×6 #2 Douglas Fir	9.3	9.7	9.6	10.2	9.4	9.64	11/20/2018
2×4 #2 Douglas Fir	8.6	8	9.3	7.8	9.1	8.56	11/20/2018
1×6 construction Douglas Fir	9.3	9.5	10.3	10.8	10.4	10.06	11/20/2018

Moisture content readings (%)							
Lumber section	**Moisture Content Readings (%)**					**Average (%)**	**Date**
2×6 #2 Douglas Fir	9.2	10.5	11.2	10.9	10.7	10.50	2/5/2019
2×4 #2 Douglas Fir	8.7	9.6	9.4	9.8	9.9	9.48	2/5/2019
1×6 construction Douglas Fir	8.6	8.4	9.3	7.8	7.6	8.34	2/5/2019

Test 22 – Specimen A-18							
Lumber Section	**Moisture content readings (%)**					**Average (%)**	**Date**
2×6 #2 Douglas Fir	10.4	10	9.8	11.2	10.9	10.46	2/12/2019
2×4 #2 Douglas Fir	8.7	9.6	9.8	9.2	8.8	9.22	2/12/2019
1×6 construction Douglas Fir	8.6	8.2	8	8.9	9.1	8.56	2/12/2019

Table A.2 Moisture content readings of Phase 4 lumber used in construction.

Construction Phase 4							
Lumber section	Moisture content readings (%)					Average (%)	Date
2×6 #2 Douglas Fir	12.6	14.2	13.5	13	12.7	13.20	8/2/2019
2×4 #2 Douglas Fir	12.6	13.5	13.4	12.6	12.8	12.98	8/2/2019
1×6 Redwood Shiplap Siding	10.4	9.8	7.9	9.6	8.8	9.30	8/2/2019
1×6 Construction Douglas Fir	14.3	12.8	12.7	13.6	13.6	13.40	8/2/2019

Test 26 – Specimen A-27							
Lumber section	Moisture content readings (%)					Average (%)	Date
2×6 #2 Douglas Fir	11.2	10.3	11.1	10.2	9.4	10.44	10/22/2018
2×4 #2 Douglas Fir	9.8	8.7	10.2	11.3	9.7	9.94	10/22/2018
1×6 Construction Douglas Fir	13.2	11.4	11.2	12.1	10.6	11.70	10/22/2018

Test 27 – Specimen A-25							
Lumber section	Moisture content readings (%)					Average (%)	Date
2×6 #2 Douglas Fir	11.3	9.5	9.3	10.4	10.1	10.12	10/29/2019
2×4 #2 Douglas Fir	8.9	8.4	10.3	10.1	9	9.34	10/29/2019

Test 28 – Specimen A-26							
Lumber Section	Moisture Content Readings (%)					Average (%)	Date
2×6 #2 Douglas Fir	10.9	10.5	10.2	9.3	9.4	10.06	11/7/2019
2×4 #2 Douglas Fir	8.6	9.6	9.2	8.9	8.9	9.04	11/7/2019

A.2 STUCCO COMPRESSIVE STRENGTH

During the stucco application process, 2 in. × 4 in. test cylinders were filled with the stucco mix to be tested later for quality control. For each layer of stucco—scratch coat, brown coat, and finish coat—there were 9–12 samples taken. Table A.3 presents the data of Phase 3 stucco samples, and Table A.4 presents the data of Phase 4 stucco samples. Within this table is the average compressive strength of each layer on the day tested and the average compressive strength of all the samples taken for each layer regardless of day tested. For Phase 3 testing, the scratch coat average compressive strength was 2651 psi, the brown coat average compressive strength was 2899 psi, and the finish coat average compressive strength was 791 psi. For Phase 4 testing, the scratch coat average compressive strength was 2066 psi, the brown coat average compressive strength was 2899 psi, and the finish coat average compressive strength was 1616 psi. Since the composition of the scratch coat and the brown coat are similar, their compressive strength values should be comparable. The difference between the two can be largely attributed to the increased curing time of the scratch coat versus the brown coat. The finish coat is expected to be weaker than the scratch and brown coats due to the increased amount of hydrated lime used in the mix. The compressive strength of the stucco for Phases 3 and 4 of testing were significantly greater than those of Phase 1, even though the materials and mix composition were identical. The difference can be attributed to the cylinders not being properly tamped down, which resulted in large air pockets being present in the samples after curing. The details of the stucco mix and application are presented in the first report [Schiller et al. 2020(a)].

Table A.3 Compressive strengths of Phase 3 stucco.

Cylinder label	Test date	Days after installation	Vertical load (kips)	Compressive strength (psi)
Scratch coat layer installed on 6/11/2018				
Scratch Coat 1	7/19/2019	38	6.66	2120
Scratch Coat 2	7/19/2019	38	8.43	2683
Scratch Coat 3	7/19/2019	38	7.62	2426
Scratch Coat 4	7/19/2019	38	8.13	2588
Scratch Coat 5	7/19/2019	38	7	2228
Scratch Coat 6	7/19/2019	38	9.87	3142
Scratch Coat 7	7/19/2019	38	8.63	2747
Scratch Coat 8	7/19/2019	38	10.08	3209
Scratch Coat 9	7/19/2019	38	6.36	2024
Scratch Coat 10	7/19/2019	38	9.06	2884
Scratch Coat 11	7/19/2019	38	9.19	2925
Scratch Coat 12	7/19/2019	38	8.92	2839
Average compressive strength (psi)				**2651**
Brown coat layer installed on 6/14/2018				
Brown Coat 1	7/19/2019	34	9.6	3056
Brown Coat 2	7/19/2019	34	7.75	2467
Brown Coat 3	7/19/2019	34	9.78	3113
Brown Coat 4	7/19/2019	34	10.26	3266
Brown Coat 5	7/19/2019	34	9.72	3094
Brown Coat 6	7/19/2019	34	7.3	2324
Brown Coat 7	7/19/2019	34	9.86	3139
Brown Coat 8	7/19/2019	34	10.87	3460
Brown Coat 9	7/19/2019	34	8.78	2795
Brown Coat 10	7/19/2019	34	7.16	2279
Brown Coat 11	7/19/2019	34	10.53	3352
Brown Coat 12	7/19/2019	34	7.69	2448
Average compressive strength (psi)				**2899**
Finish coat layer installed on 6/21/2018				
Finish Coat 1	7/19/2019	28	2.47	786
Finish Coat 2	7/19/2019	28	2.97	945
Finish Coat 3	7/19/2019	28	2.41	767
Finish Coat 4	7/19/2019	28	1.79	570
Finish Coat 5	7/19/2019	28	2.74	872
Finish Coat 6	7/19/2019	28	2.63	837
Finish Coat 7	7/19/2019	28	2.53	805
Finish Coat 8	7/19/2019	28	2.87	914
Finish Coat 9	7/19/2019	28	2.43	773
Finish Coat 10	7/19/2019	28	1.89	602
Finish Coat 11	7/19/2019	28	2.32	738
Finish Coat 12	7/19/2019	28	2.78	885
Average compressive strength (psi)				**791**

Table A.4 Compressive strengths of Phase 4 stucco.

Cylinder label	Test date	Days after installation	Vertical load (kips)	Compressive strength (psi)
Scratch coat layer installed on 10/1/2019				
Scratch Coat 1	11/7/2019	37	7.2	2293
Scratch Coat 2	11/7/2019	37	8.03	2557
Scratch Coat 3	11/7/2019	37	8.49	2704
Scratch Coat 4	11/7/2019	37	8.13	2589
Scratch Coat 5	11/7/2019	37	9.16	2917
Scratch Coat 6	11/7/2019	37	9.12	2904
Scratch Coat 7	11/7/2019	37	7.9	2516
Scratch Coat 8	11/7/2019	37	6.73	2143
Scratch Coat 9	11/7/2019	37	7.1	2261
Average compressive strength (psi)				**2543**
Brown coat layer installed on 10/4/2019				
Brown Coat 1	11/7/2019	33	6.85	2182
Brown Coat 2	11/7/2019	33	5.9	1879
Brown Coat 3	11/7/2019	33	6.5	2070
Brown Coat 4	11/7/2019	33	6.65	2118
Brown Coat 5	11/7/2019	33	6.61	2105
Brown Coat 6	11/7/2019	33	5.56	1771
Brown Coat 7	11/7/2019	33	7.29	2322
Brown Coat 8	11/7/2019	33	5.92	1885
Brown Coat 9	11/7/2019	33	7.11	2264
Average compressive strength (psi)				**2066**
Finish coat layer installed on 10/11/2019				
Finish Coat 1	11/7/2019	26	5.25	1672
Finish Coat 2	11/7/2019	26	4.36	1389
Finish Coat 3	11/7/2019	26	6.14	1955
Finish Coat 4	11/7/2019	26	4.26	1357
Finish Coat 5	11/7/2019	26	5.12	1631
Finish Coat 6	11/7/2019	26	4.38	1395
Finish Coat 7	11/7/2019	26	5.55	1768
Finish Coat 8	11/7/2019	26	5.53	1761
Finish Coat 9	7/19/2019	28	2.43	773
Average compressive strength (psi)				**791**

A.3 LOADING PROTOCOLS

The following section presents a graph and table of the loading protocol for the specimens considered in this report.

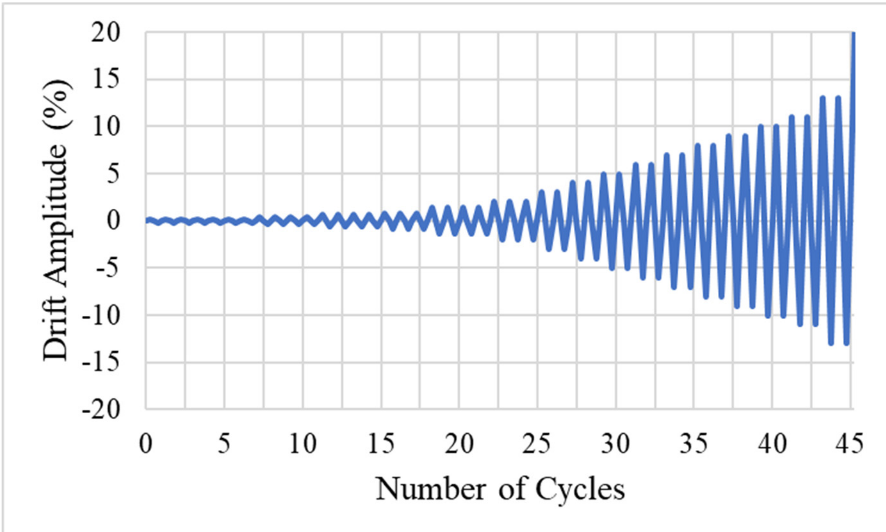


Figure A.2 Specimen A-15 loading protocol.

Table A.5 Specimen A-15 loading protocol.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	7	1.68	2	0.224	30	60
12	8	1.92	2	0.256	30	60
13	9	2.16	2	0.288	30	60
14	10	2.4	2	0.16	60	120
15	11	2.64	2	0.176	60	120
16	13	3.12	2	0.208	60	120
17	Mono	5.0	--	0.333	60	60

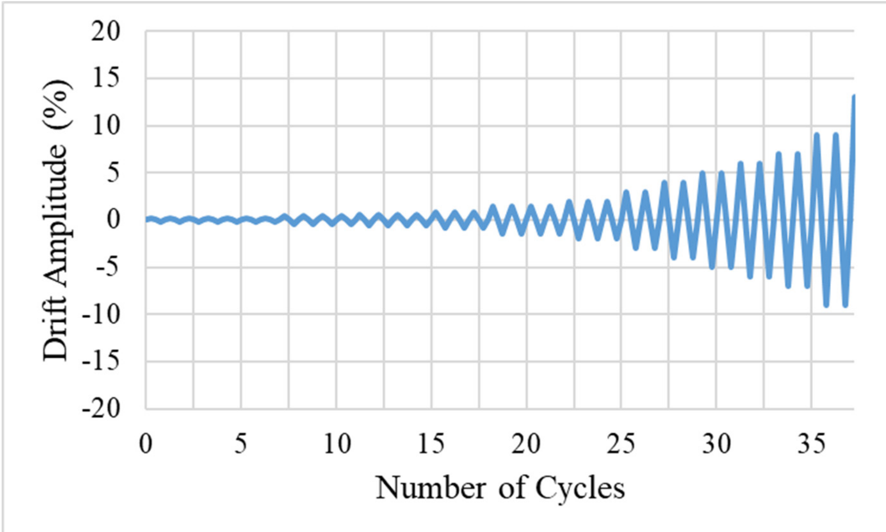


Figure A.3 Specimen A-16 loading protocol.

Table A.6 Specimen A-16 loading protocol.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	7	1.68	2	0.224	30	60
12	9	2.16	2	0.288	30	60
13	Mono	3.12	--	0.208	60	60

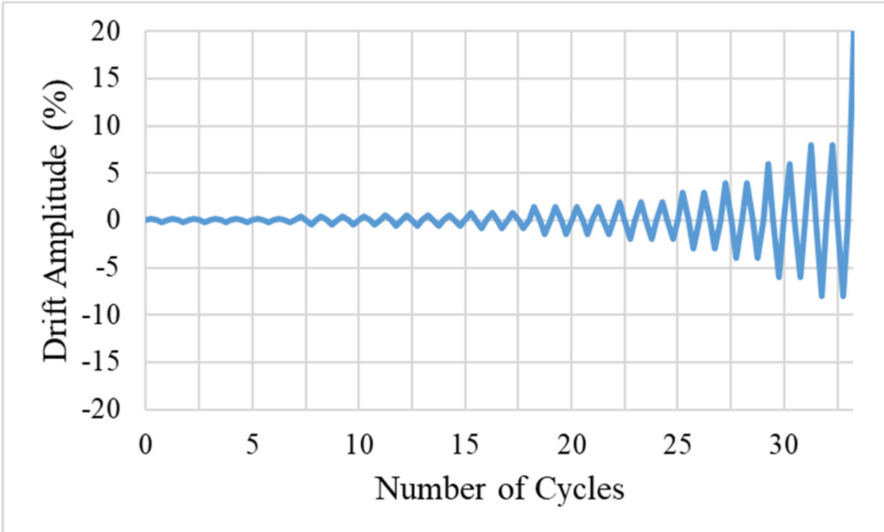


Figure A.4 Specimen A-17 loading protocol.

Table A.7 Specimen A-17 loading protocol.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	6	1.44	2	0.192	30	60
10	Mono	5	--	0.333	60	60

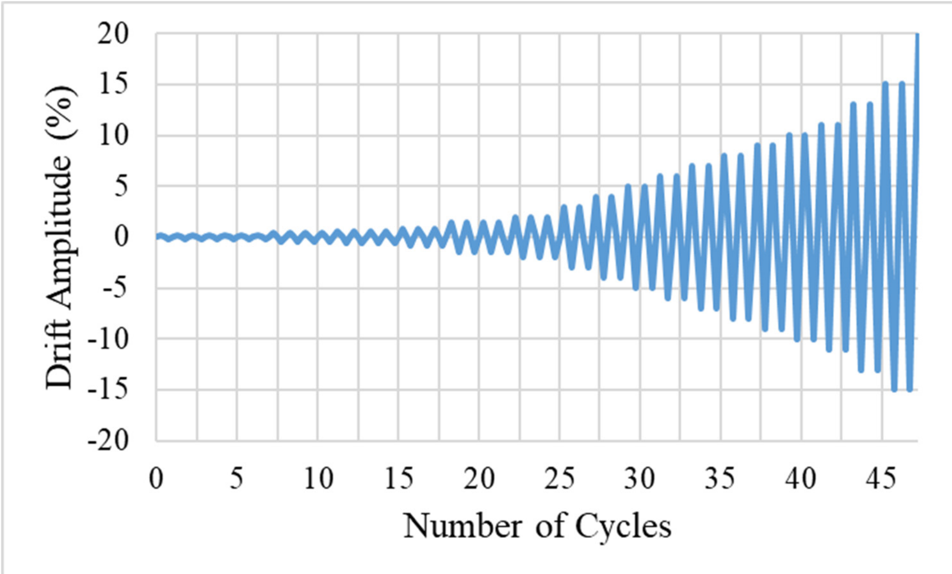


Figure A.5 Specimen A-18 loading protocol.

Table A.8 Specimen A-18 loading protocol.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	7	1.68	2	0.224	30	60
12	8	1.92	2	0.256	30	60
13	9	2.16	2	0.288	30	60
14	10	2.4	2	0.16	60	120
15	11	2.64	2	0.176	60	120
16	13	3.12	2	0.208	60	120
17	15	3.6	2	0.24	60	120
18	Mono	5.0	--	0.333	60	60

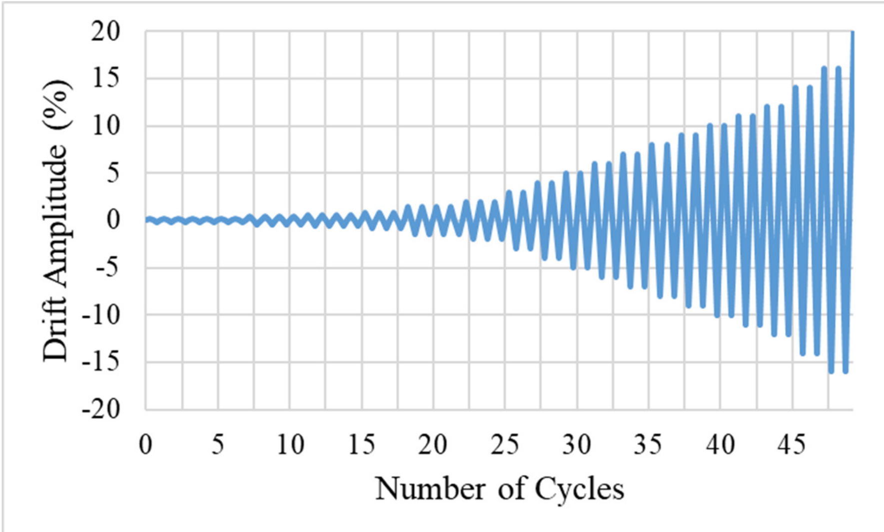


Figure A.6 Specimen A-19 loading protocol.

Table A.9 Specimen A-19 loading protocol.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	7	1.68	2	0.224	30	60
12	8	1.92	2	0.256	30	60
13	9	2.16	2	0.288	30	60
14	10	2.4	2	0.16	60	120
15	11	2.64	2	0.176	60	120
16	12	2.88	2	0.192	60	120
17	14	3.36	2	0.224	60	120
18	16	3.84	2	0.256	60	120
19	Mono	5.0	--	0.333	60	60

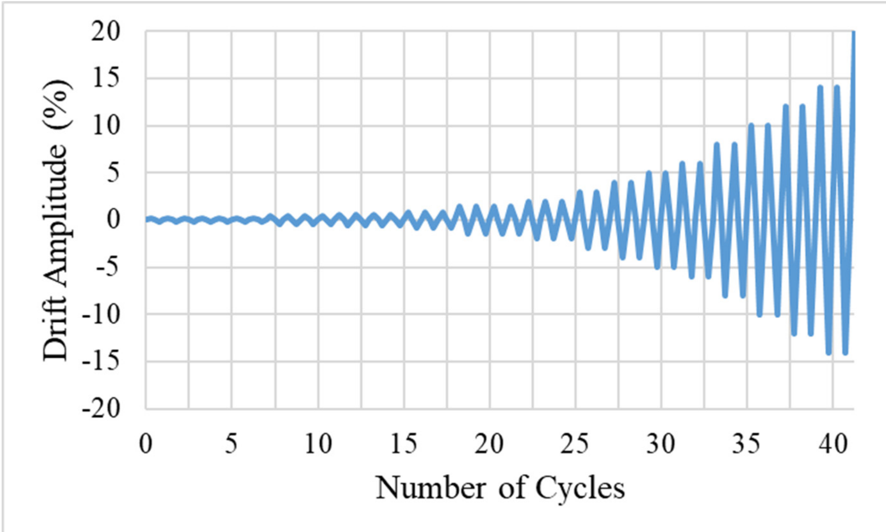


Figure A.7 Specimen A-20 loading protocol.

Table A.10 Specimen A-20 loading protocol.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	14	3.36	2	0.224	60	120
15	Mono	5.0	--	0.333	60	60

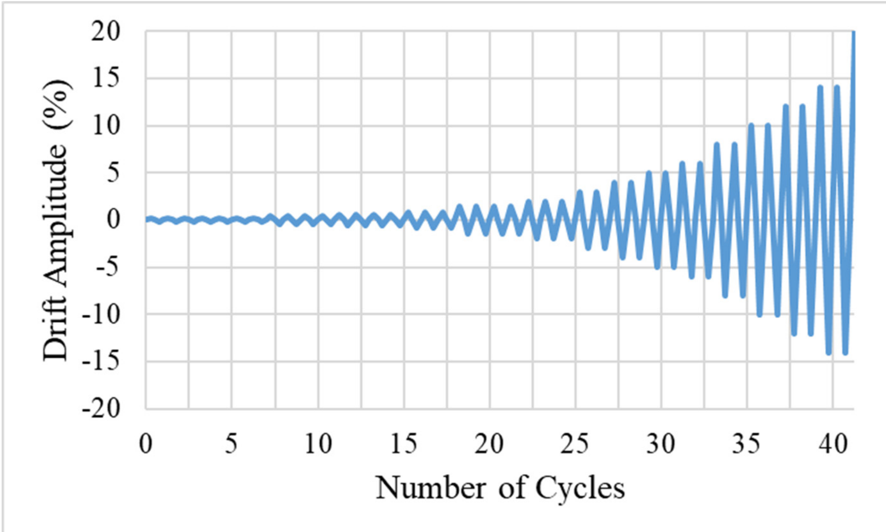


Figure A.8 Specimen A-21 loading protocol.

Table A.11 Specimen A-21 loading protocol.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	14	3.36	2	0.224	60	120
15	Mono	5.0	--	0.333	60	60

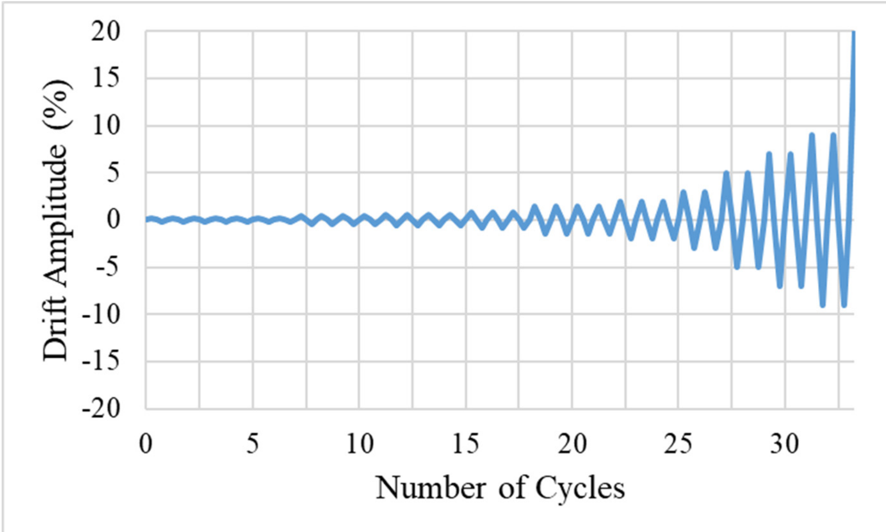


Figure A.9 Specimen A-22 loading protocol.

Table A.12 Specimen A-22 loading protocol.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	5	1.2	2	0.16	30	60
9	7	1.68	2	0.224	30	60
10	9	2.16	2	0.288	30	60
13	Mono	5	--	0.333	60	60

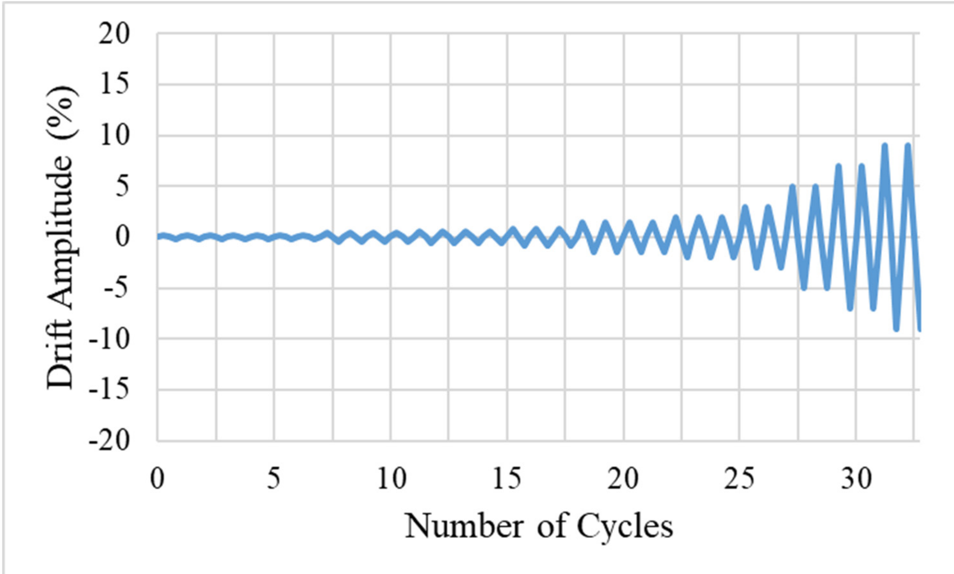


Figure A.10 Specimen A-25 loading protocol.

Table A.13 Specimen A-25 loading protocol.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	9	6.48	2	0.216	120	240

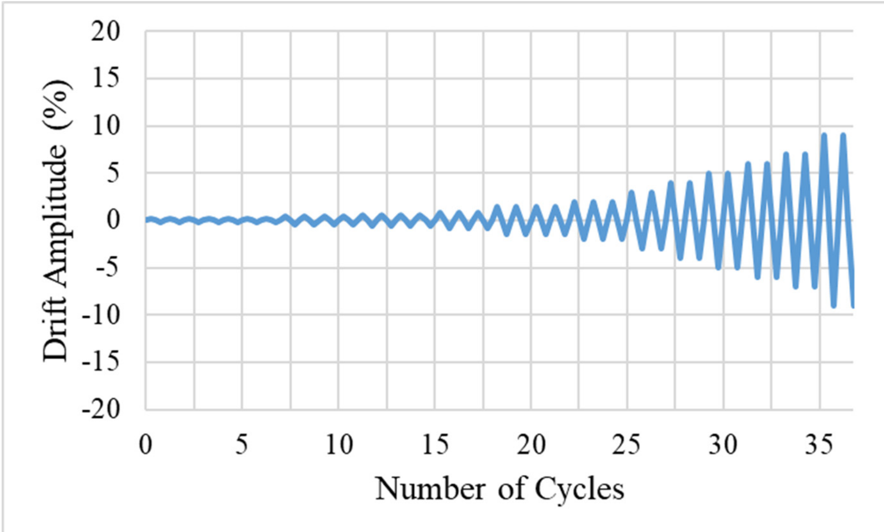


Figure A.11 Specimen A-26 loading protocol.

Table A.14 Specimen A-26 loading protocol.

Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig 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	5	3.6	2	0.24	60	120
9	7	5.04	2	0.336	60	120
10	9	6.48	2	0.216	120	240

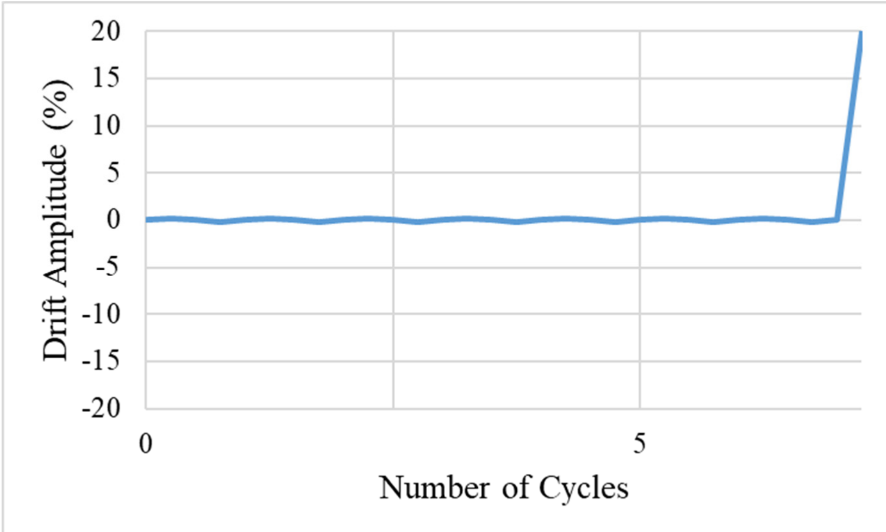


Figure A.12 Specimen A-27 loading protocol.

Table A.15 Specimen A-27 loading protocol.

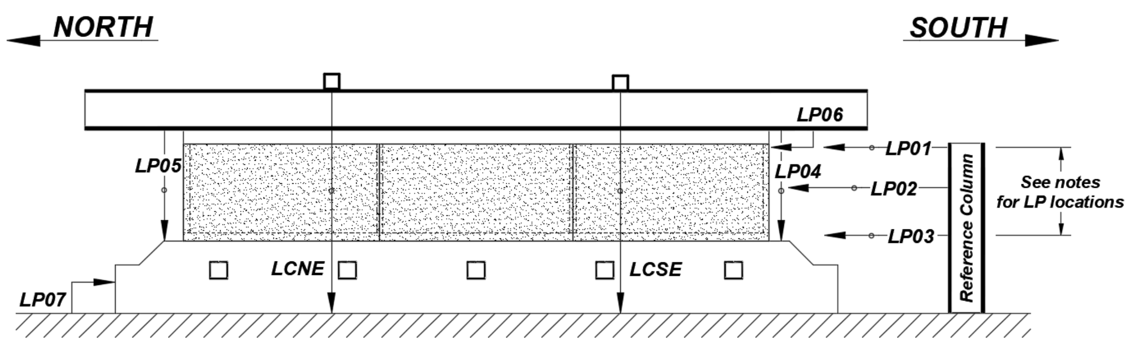
Cycle group no.	Drift (%)	Amplitude (in.)	No. of cycles per group	Loadig rate (in./sec)	Time per cycle (sec)	Total time per cycle group (sec)
1	0.2	0.048	7	0.0064	30	210
2	Mono	5	--	0.333	60	60

Appendix B Test Setup

Appendix B includes two sections: construction drawings (B.1) and instrumentation plans for testing (B.2). Discussion of these sections is provided in Chapter 3.

B.1 INSTRUMENTATION DRAWINGS

B.1.1 Specimen A-15 Instrumentation Drawings

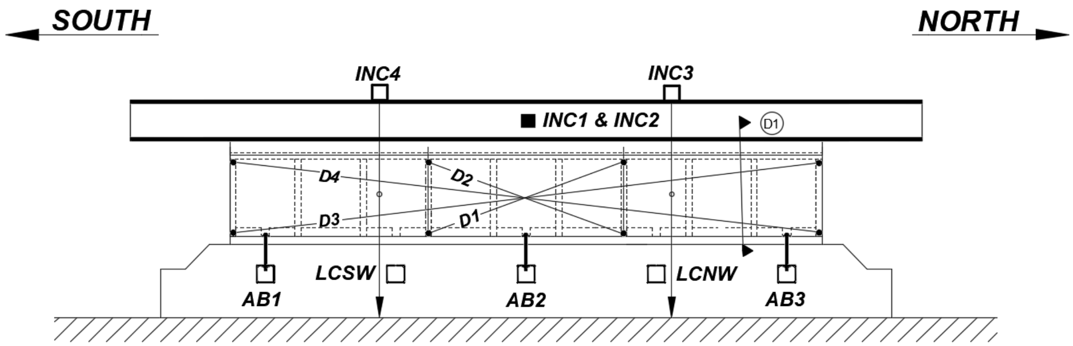


Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of upper top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LCNE and LCSE monitor the axial load on the East Side of the wall.

Instrumentation Elevation E1
Stucco Face
2' Tall Cripple Wall

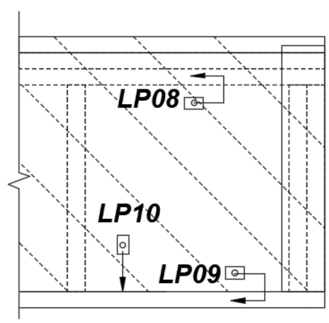
Figure B.1 Specimen A-15 instrumentation.



Notes:

1. AB1-AB5 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. INC3 and INC4 measure the rotation of the transverse beams where axial load is applied.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation E2
Framing Face
2' Tall Cripple Wall



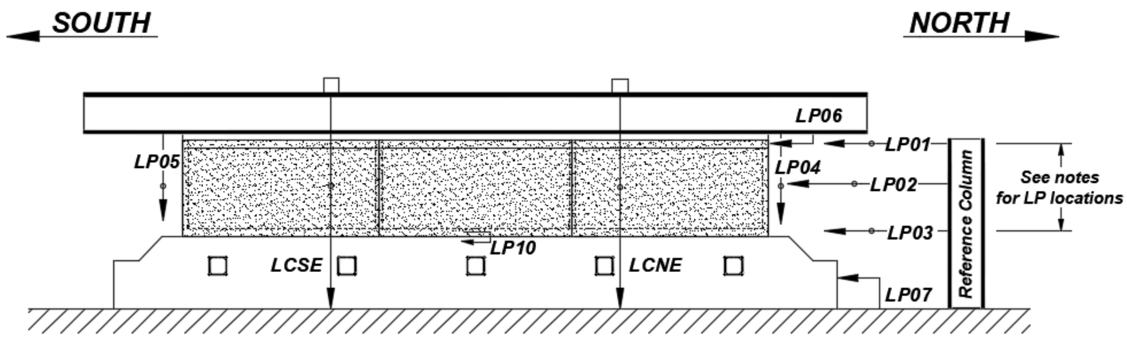
Notes:

1. LP08 and LP09 monitor the sheathing slip.
2. LP10 monitors the sheathing uplift

Instrumentation Detail D1
Sheathing

Figure B.1 (continued).

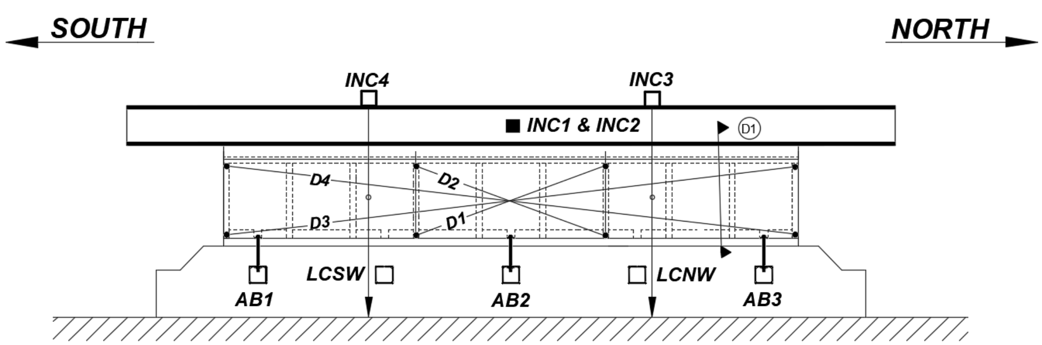
B.1.2 Specimen A-16 Instrumentation Drawings



Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of upper top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LCNE and LCSE monitor the axial load on the East Side of the wall.
6. LP10 monitors displacement of stucco relative to the footing.

Instrumentation Elevation E1
Stucco Face
2' Tall Cripple Wall

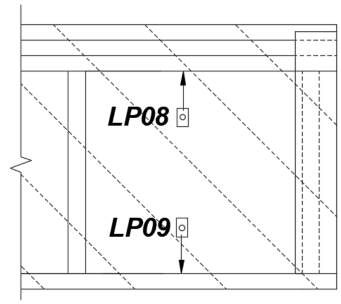


Notes:

1. AB1-AB5 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. INC3 and INC4 measure the rotation of the transverse beams where axial load is applied.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation E2
Framing Face
2' Tall Cripple Wall

Figure B.2 Specimen A-16 instrumentation.

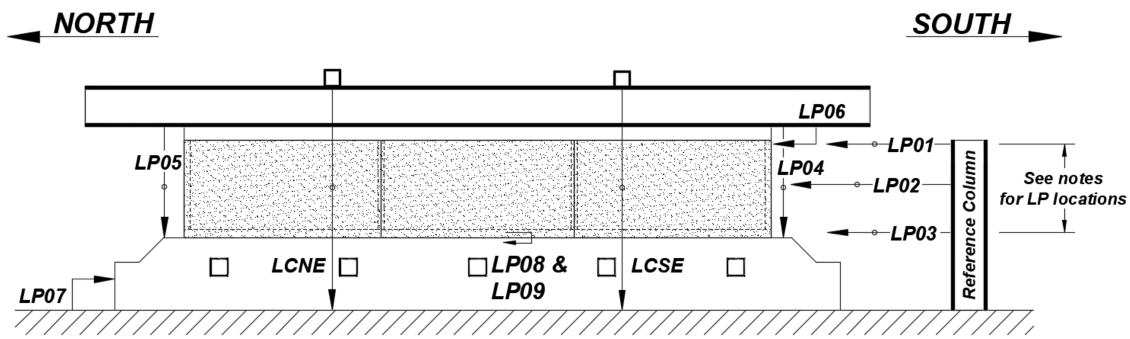


Notes:
1. **LP08 and LP09 monitor the siding slip.**

Instrumentation Detail D1
Siding

Figure B.2 (continued).

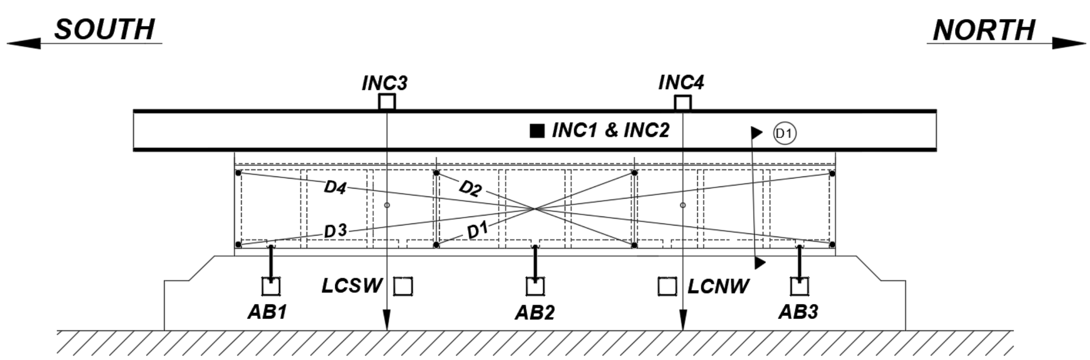
B.1.3 Specimen A-17 Instrumentation Drawings



Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of upper top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LP08 monitors the horizontal displacement of the stucco base.
6. LP09 monitors the lateral displacement of the stucco base.
7. LCNE and LCSE monitor the axial load on the East Side of the wall.

Instrumentation Elevation E1
Stucco Face
2' Tall Cripple Wall



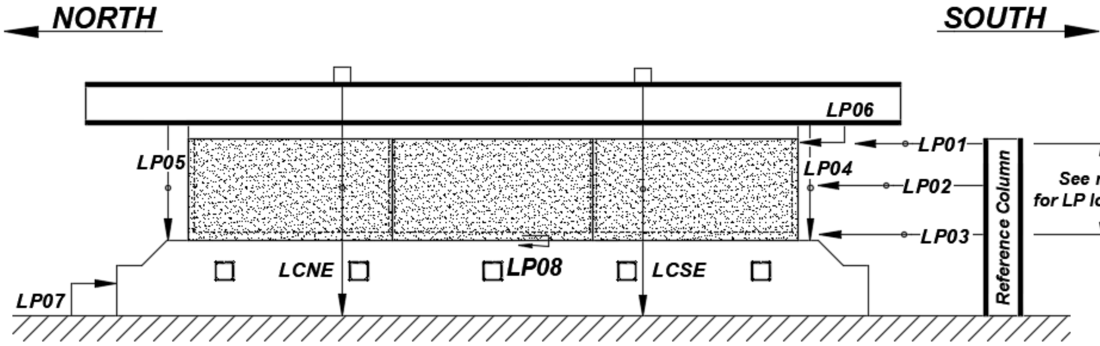
Notes:

1. AB1-AB5 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. INC3 and INC4 measure the rotation of the transverse beams where axial load is applied.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation E2
Framing Face
2' Tall Cripple Wall

Figure B.3 Specimen A-17 instrumentation.

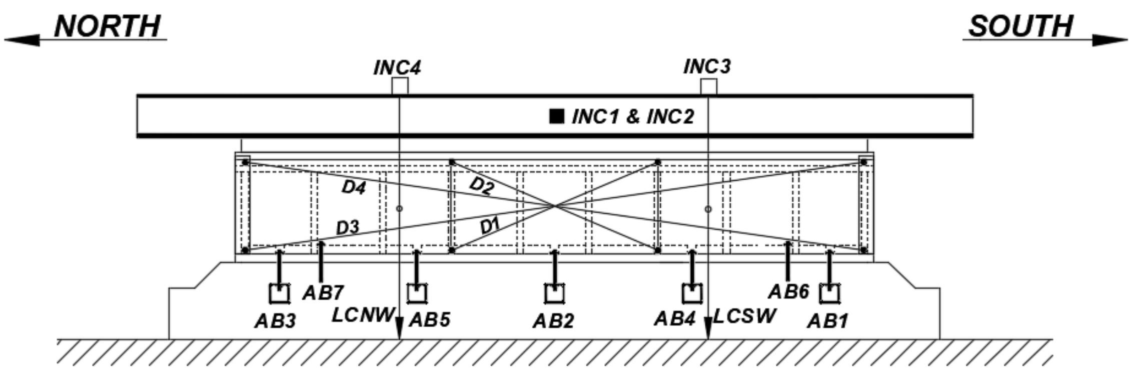
B.1.4 Specimen A-18 Instrumentation Drawings



Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of upper top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LP08 monitors the horizontal displacement of the stucco base.
6. LCNE and LCSE monitor the axial load on the East Side of the wall.

Instrumentation Elevation (E1)
Stucco Face
2' Tall Cripple Wall



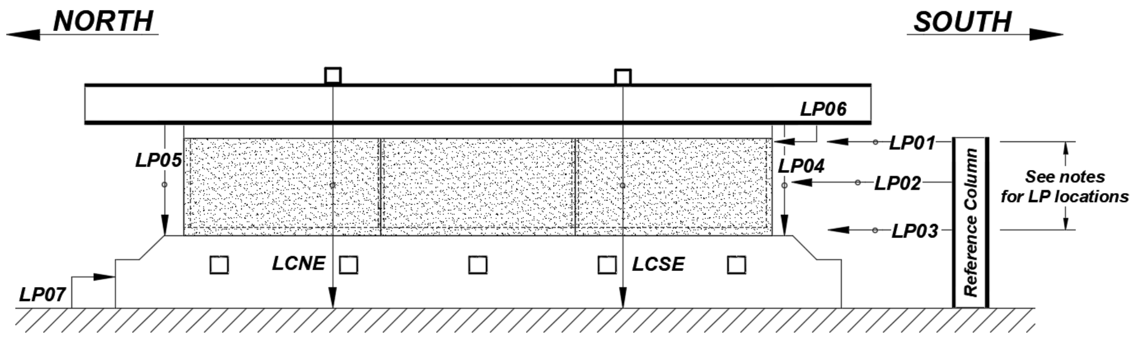
Notes:

1. AB1-AB7 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. INC3 and INC4 measure the rotation of the transverse beams where axial load is applied.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation (E2)
Framing Face
2' Tall Cripple Wall

Figure B.4 Specimen A-18 instrumentation.

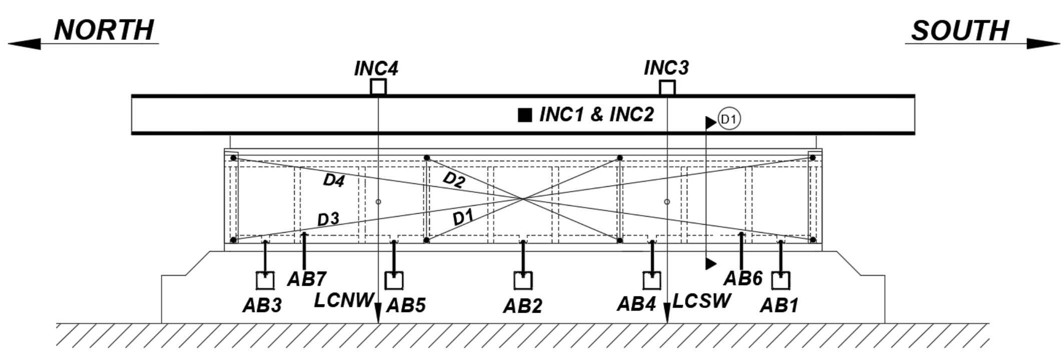
B.1.5 Specimen A-19 Instrumentation Drawings



Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of upper top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LCNE and LCSE monitor the axial load on the East Side of the wall.

Instrumentation Elevation E1
Stucco Face
2' Tall Cripple Wall

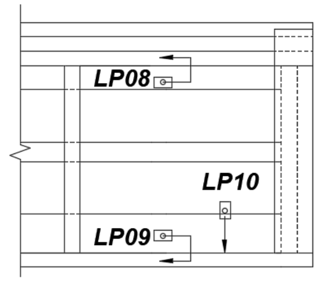


Notes:

1. AB1-AB7 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. INC3 and INC4 measure the rotation of the transverse beams where axial load is applied.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation E2
Framing Face
2' Tall Cripple Wall

Figure B.5 Specimen A-19 instrumentation.



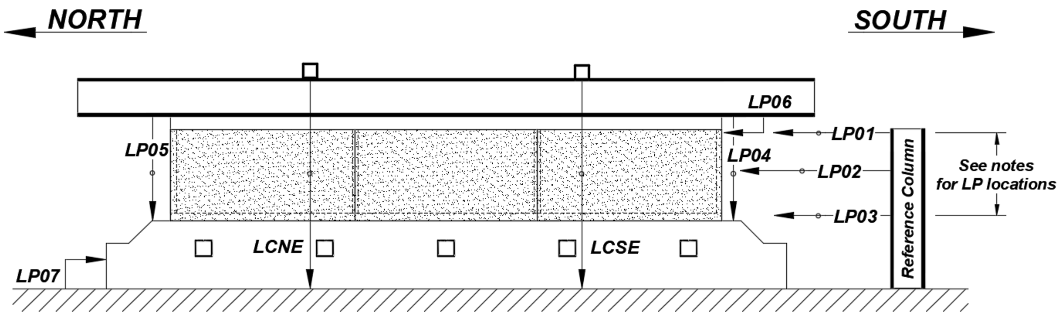
Notes:

1. **LP08 and LP09 monitor the siding slip.**
2. **LP10 monitors the uplift of the bottom sheathing board.**

Instrumentation Detail D1
Siding

Figure B.5 (continued).

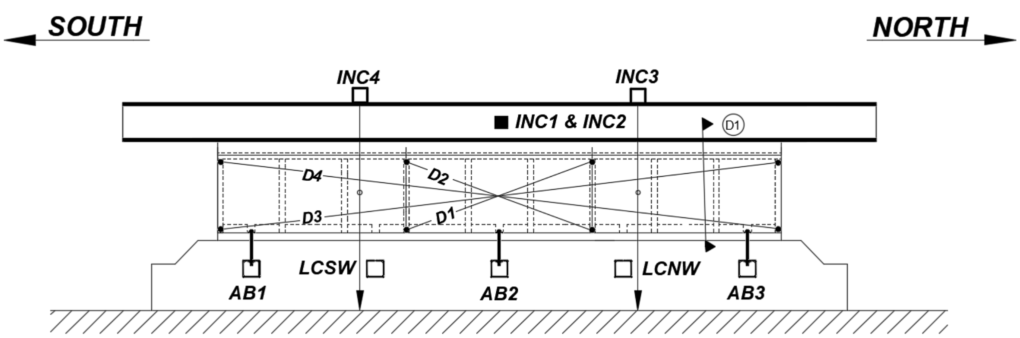
B.1.6 Specimen A-20 Instrumentation Drawings



Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of upper top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LCNE and LCSE monitor the axial load on the East Side of the wall.

Instrumentation Elevation E1
Stucco Face
2' Tall Cripple Wall

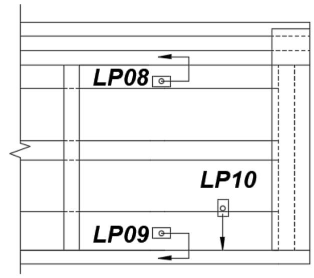


Notes:

1. AB1-AB5 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. INC3 and INC4 measure the rotation of the transverse beams where axial load is applied.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation E2
Framing Face
2' Tall Cripple Wall

Figure B.6 Specimen A-20 instrumentation.



Notes:

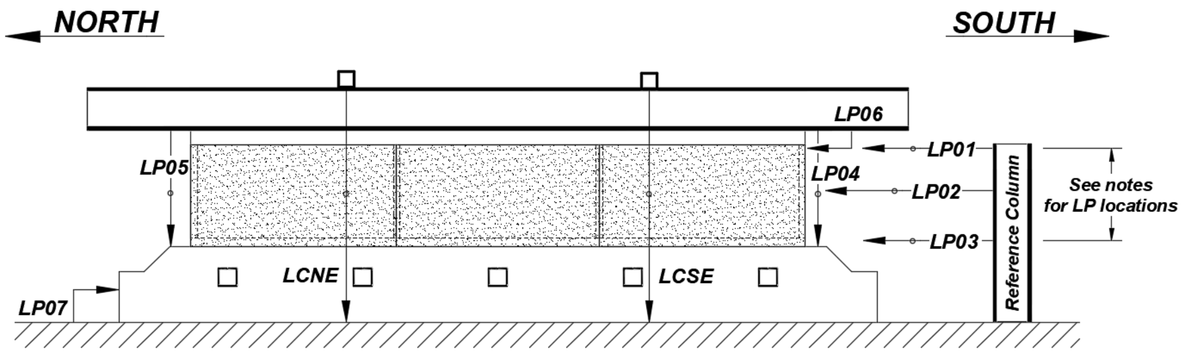
1. **LP08 and LP09 monitor the siding slip.**
2. **LP10 monitors the uplift of the bottom sheathing board.**

Instrumentation Detail D1

Siding

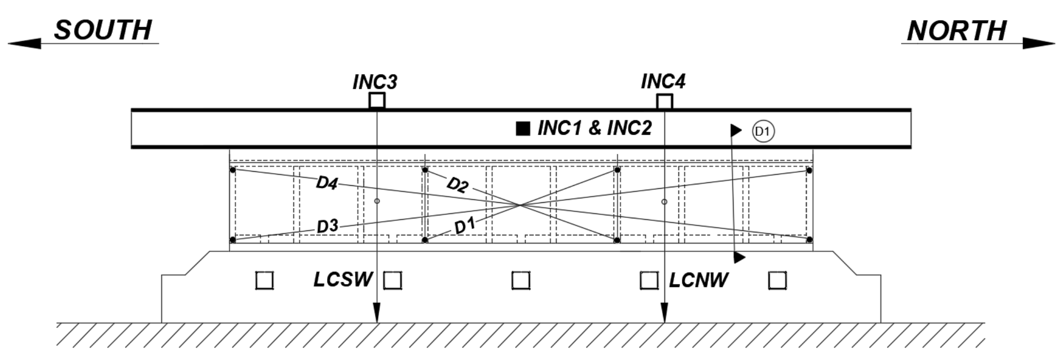
Figure B.6 (continued).

B.1.7 Specimen A-21 Instrumentation Drawings



Notes:
1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of upper top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LCNE and LCSE monitor the axial load on the East Side of the wall.

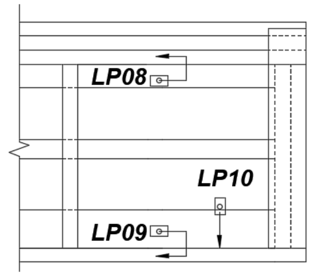
Instrumentation Elevation (E1)
Stucco Face
2' Tall Cripple Wall



Notes:
1. Pairs of string potentiometers are mounted on framing studs or plywood panels for retrofit cases.
2. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
3. INC3 and INC4 measure the rotation of the transverse beams where axial load is applied.
4. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation (E2)
Framing Face
2' Tall Cripple Wall

Figure B.7 Specimen A-21 instrumentation.

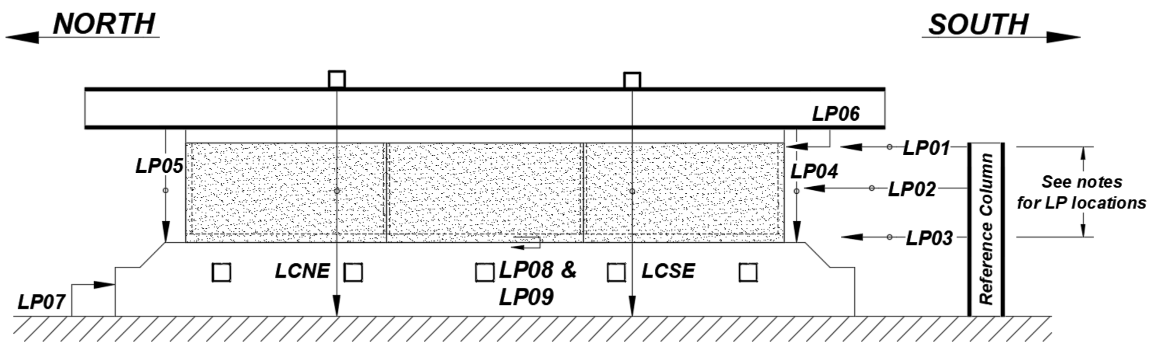


Notes:
1. LP08 and LP09 monitor the siding slip.
2. LP10 monitors the uplift of the bottom sheathing board.

Instrumentation Detail D1
Siding

Figure B.7 (continued).

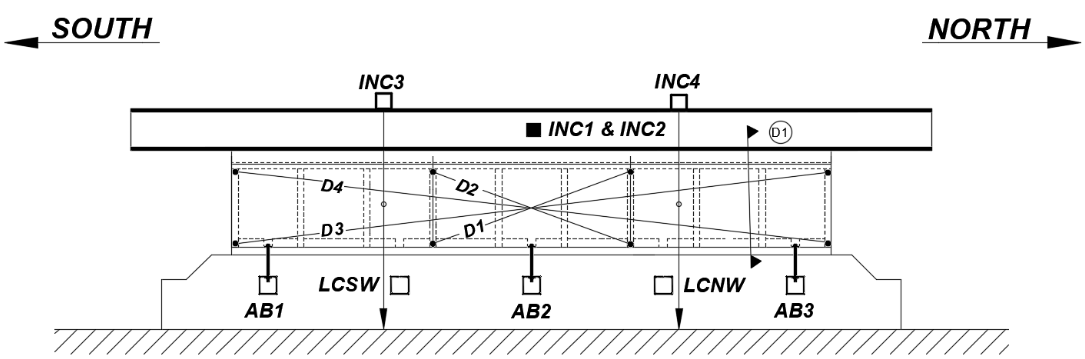
B.1.8 Specimen A-22 Instrumentation Drawings



Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of upper top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LP08 monitors the horizontal displacement of the stucco base.
6. LP09 monitors the lateral displacement of the stucco base.
7. LCNE and LCSE monitor the axial load on the East Side of the wall.

Instrumentation Elevation E1
Stucco Face
2' Tall Cripple Wall



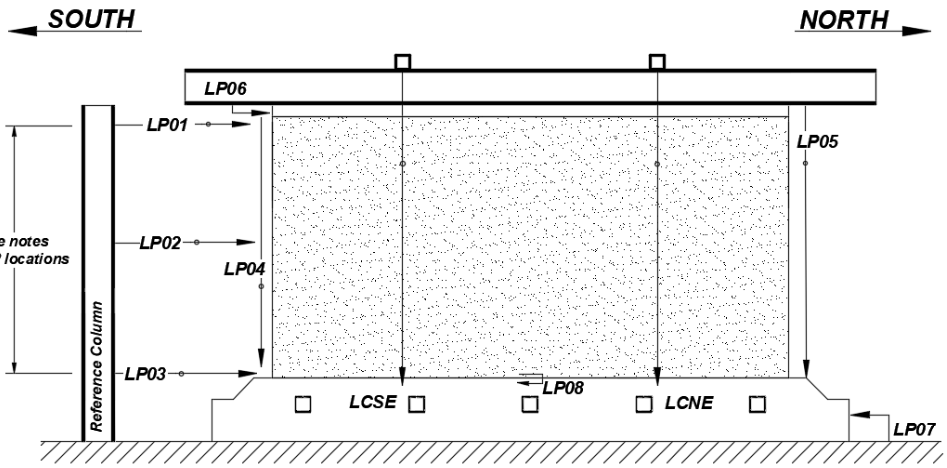
Notes:

1. AB1-AB5 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. INC3 and INC4 measure the rotation of the transverse beams where axial load is applied.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation E2
Framing Face
2' Tall Cripple Wall

Figure B.8 Specimen A-22 instrumentation.

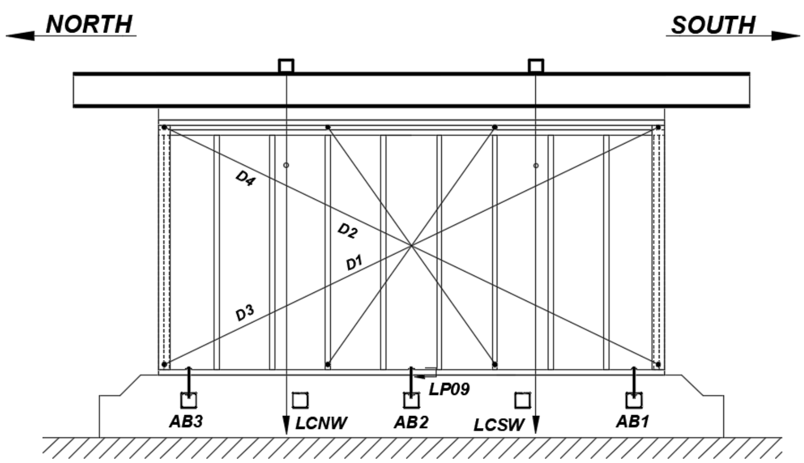
B.1.9 Specimen A-25 Instrumentation Drawings



Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of second top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LCNE and LCSE monitor the axial load on the East Side of the wall.
6. LP08 monitors displacement of stucco at the sill plate relative to the foundation.

Instrumentation Elevation E1
Finish Face
6' Tall Existing Cripple Wall
Stucco Only



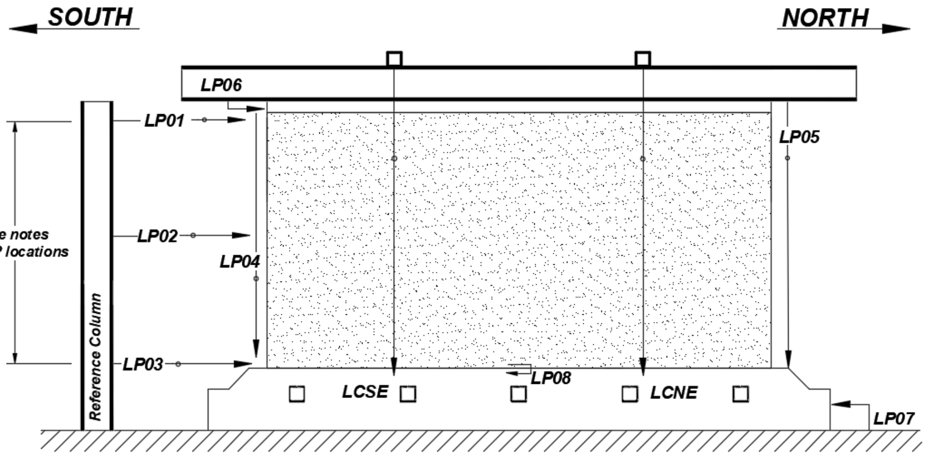
Notes:

1. D1-D4 measure the diagonal distortion of the cripple wall.
2. AB1-AB3 monitor the anchor bolt loads.
3. LP09 measures the transverse displacement of the stucco relative to the sill plate.
4. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation E2
Framing Face
6' Tall Existing Cripple Wall
Stucco Only

Figure B.9 Specimen A-25 instrumentation.

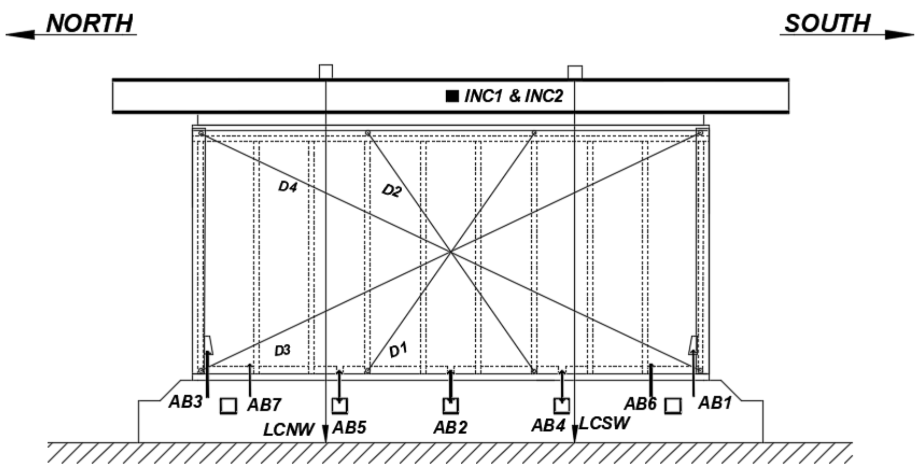
B.1.10 Specimen A-26 Instrumentation Drawings



Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of second top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LCNE and LCSE monitor the axial load on the East Side of the wall.
6. LP08 monitors displacement of stucco at the sill plate relative to the foundation.

Instrumentation Elevation (E1)
Finish Face
6' Tall Existing Cripple Wall
Stucco Only



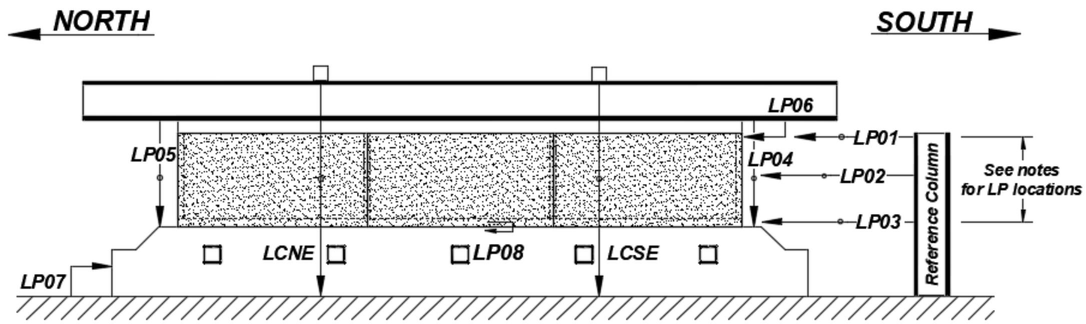
Notes:

1. AB1-AB7 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. Pairs of strength potentiometers are mounted on framing studs or plywood panels for retrofit cases.
3. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
4. D1-D4 measure the diagonal distortion of the wall.
5. LCNW and LCSW monitor the axial load on the West Side of the wall.

Instrumentation Elevation (E2)
Framing Face
6' Tall Cripple Wall

Figure B.10 Specimen A-26 instrumentation.

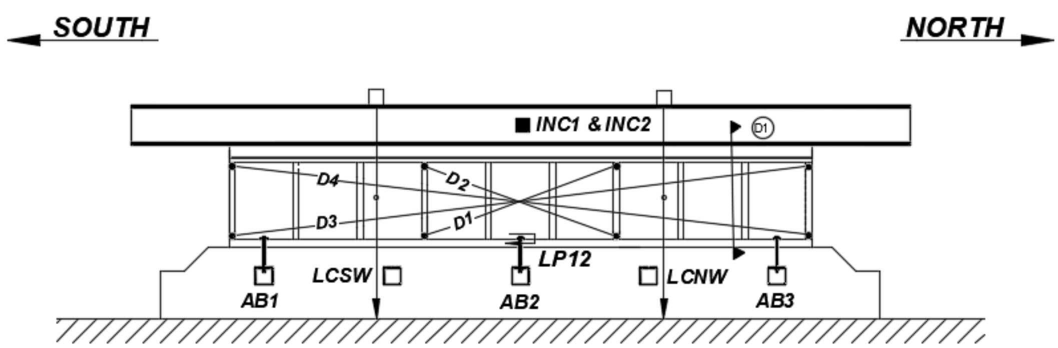
B.1.11 Specimen A-27 Instrumentation Drawings



Notes:

1. LP01, LP02, and LP03 measure lateral displacement with LP01 attached to middle of upper top plate, LP02 attached to middle of stud, and LP03 attached to middle of sill plate.
2. LP04 and LP05 measure the uplift at each end of the wall.
3. LP06 monitors the slip between the horizontal transfer beam and the upper top plate.
4. LP07 monitors the slip of the footing.
5. LP08 monitors the horizontal displacement of the stucco base.
6. LP09 monitors the lateral displacement of the stucco base.
7. LCNE and LCSE monitor the axial load on the East Side of the wall.

Instrumentation Elevation (E1)
Stucco Face
2' Tall Cripple Wall

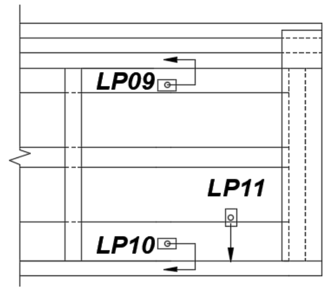


Notes:

1. AB1-AB3 are instrumented with 2" Ø Donut Load Cells measuring uplift loads.
2. INC1 measures longitudinal rotation of load transfer beam. INC2 measures the transverse rotation of the load transfer beam.
3. LCNW and LCSW monitor the axial load on the West Side of the wall.
4. D1-D4 measure the diagonal distortion of the wall.
5. LP12 measures the transverse displacement of the bottom sheathing board.

Instrumentation Elevation (E2)
Framing Face
2' Tall Cripple Wall

Figure B.11 Specimen A-27 instrumentation.



Notes:

1. **LP09 and LP10 monitor the siding slip.**
2. **LP11 monitors the uplift of the bottom sheathing board.**

Instrumentation Detail (D1)

Siding

Figure B.11 (continued).

Appendix C Test Results

Appendix C includes three sections: anchor bolt load measurements (C.1), diagonal distortion measurements (C.2), uplift measurements (C.3). Discussion of these sections is provided in Chapter 4.

C.1 ANCHOR BOLT MEASUREMENTS

Tension in anchor bolts were measured with 10-kip donut load cells placed on top of the square plate washers. A spherical washer was placed on top of the load cell and fastened with a nut. For existing cripple walls, three anchor bolts were used, spaced at 64 in. on center. The anchor bolt layout for these cripple walls can be seen in Figure 4.35. For retrofitted cripple walls, additional anchor bolts were added as per the *FEMA P-1100* prescriptive retrofit guidelines. Anchor bolts were tensioned to around 0.2 kips intended to mimic a hand-tightened amount of tension and representative of what would commonly be observed in the field for older homes.

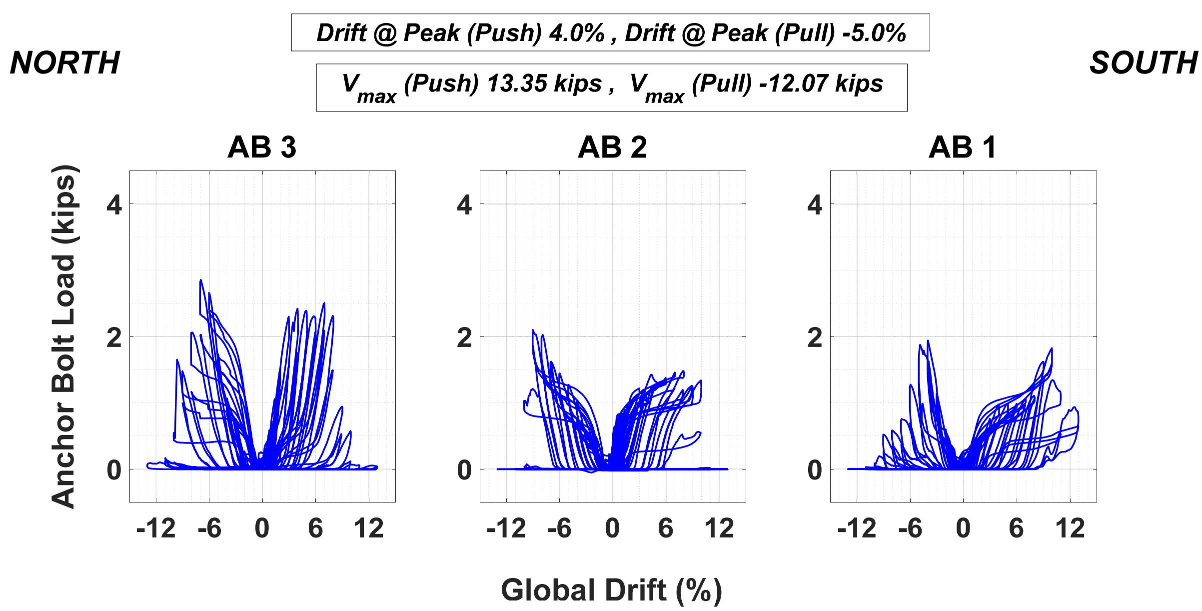


Figure C.1 Specimen A-15 anchor bolt loads versus global drift.

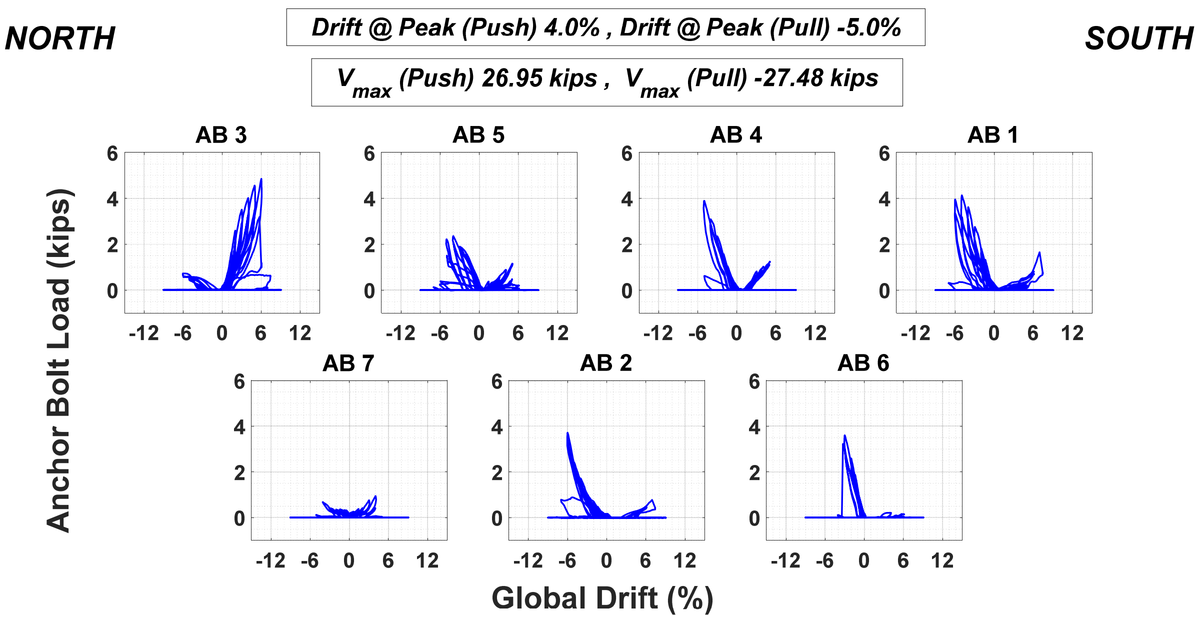


Figure C.2 Specimen A-16 anchor bolt loads versus global drift.

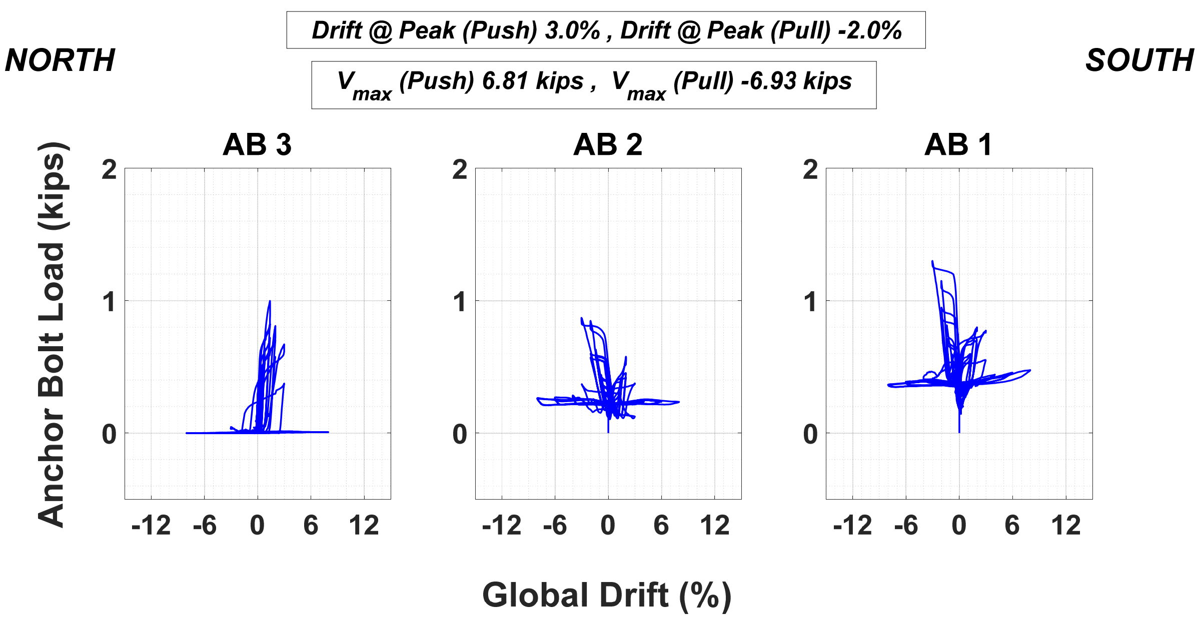


Figure C.3 Specimen A-17 anchor bolt loads versus global drift.

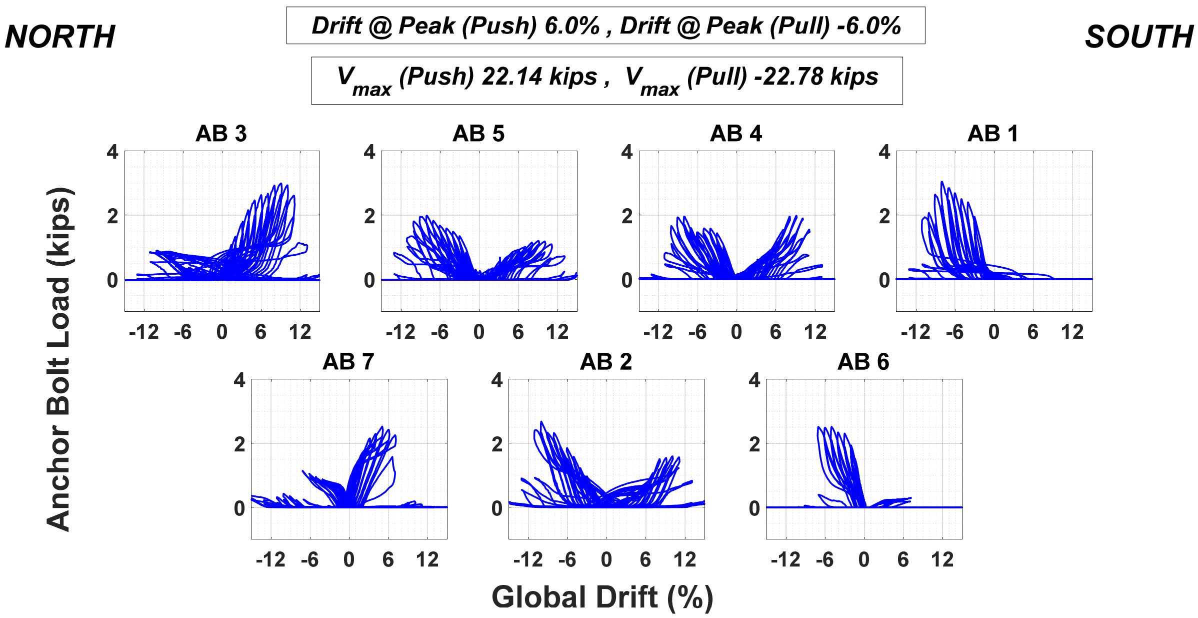


Figure C.4 Specimen A-18 anchor bolt loads versus global drift.

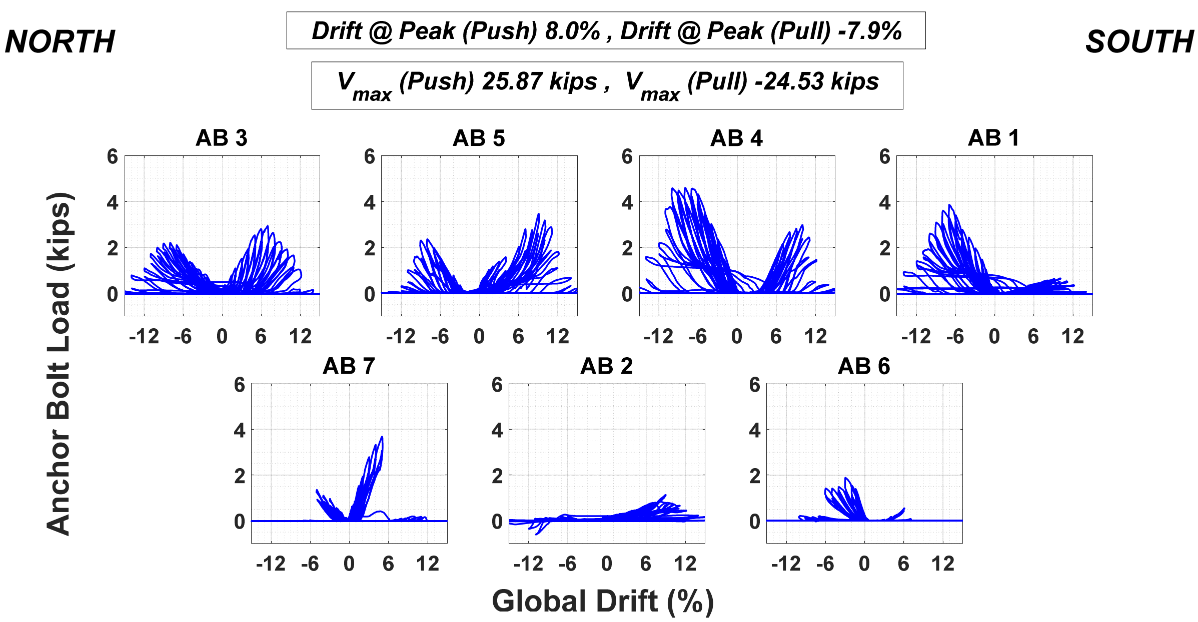


Figure C.5 Specimen A-19: anchor bolt loads versus global drift.

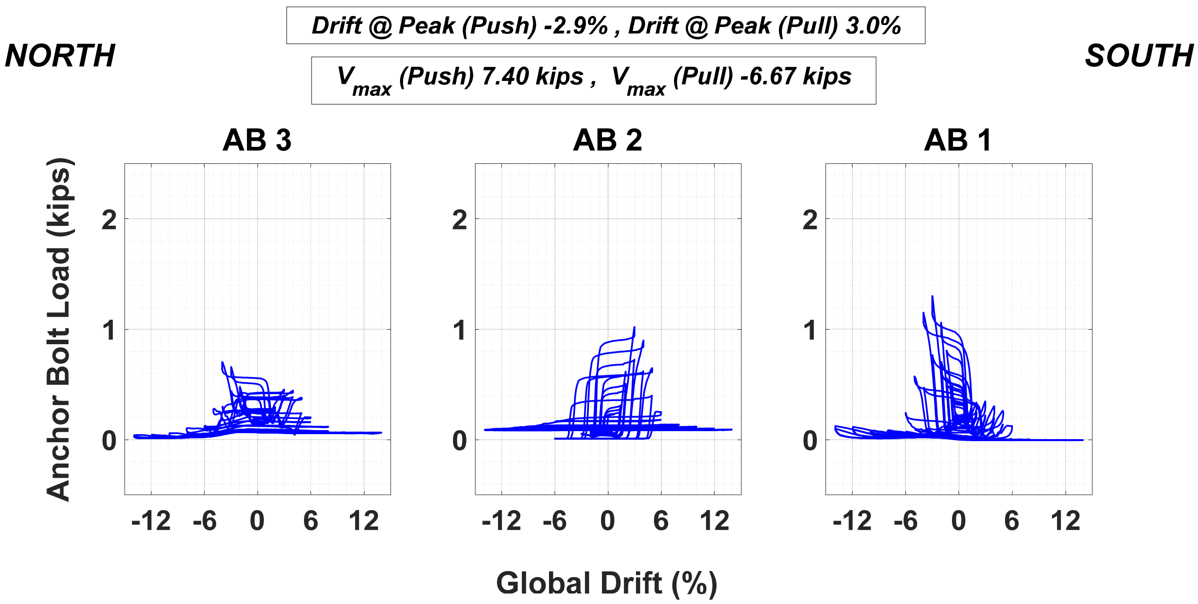


Figure C.6 Specimen A-20 anchor bolt loads versus global drift.

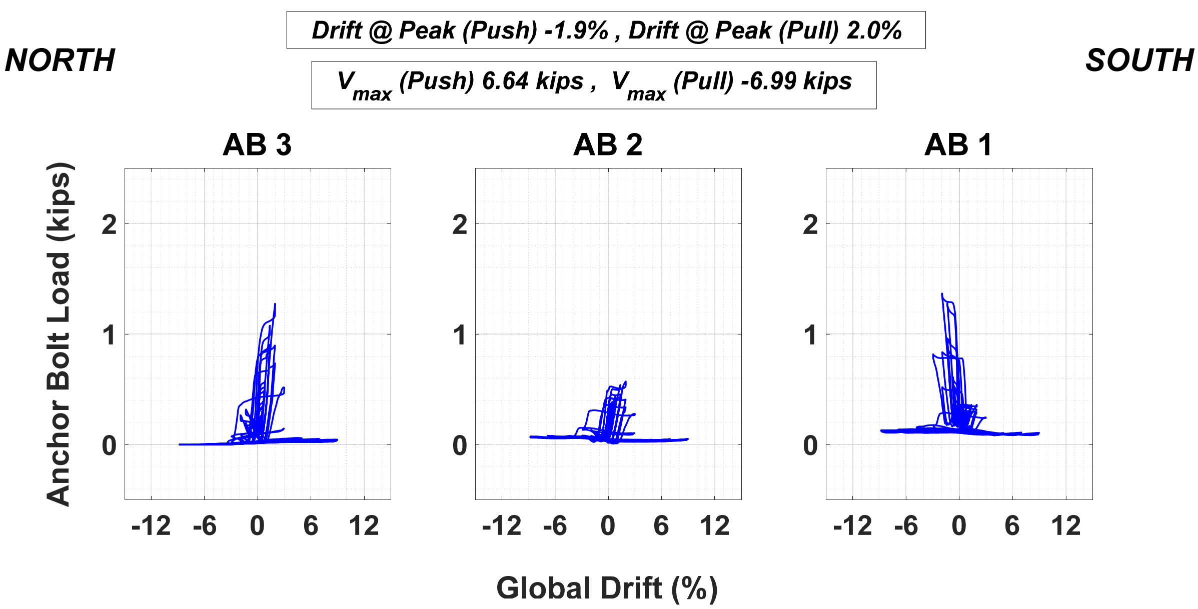


Figure C.7 Specimen A-22 anchor bolt loads versus global drift.

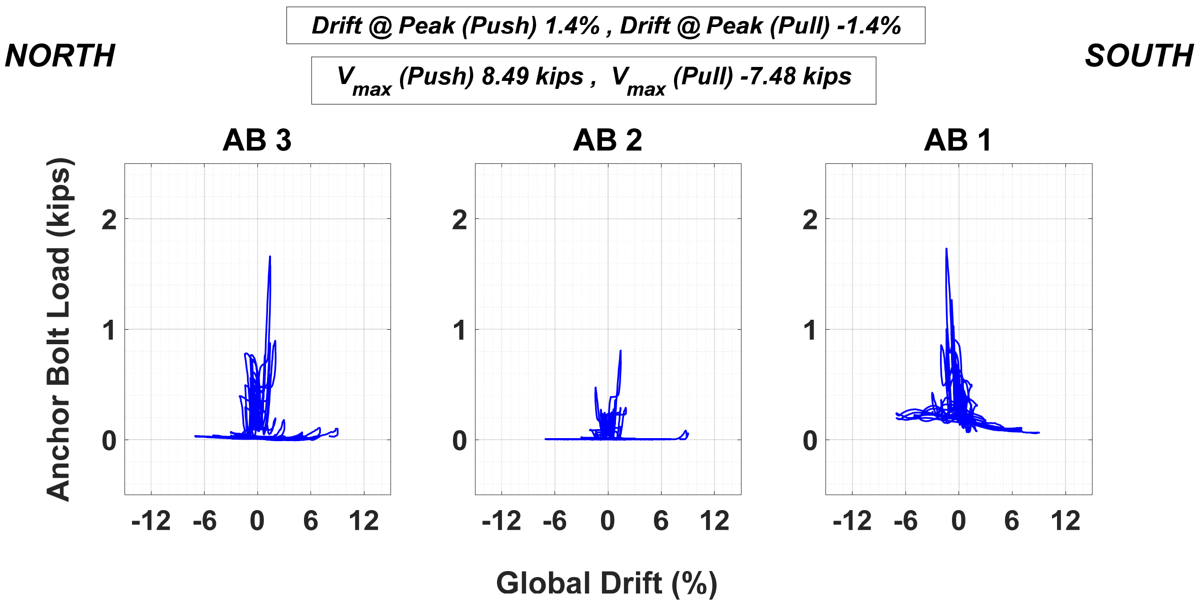


Figure C.8 Specimen A-25 anchor bolt loads versus global drift.

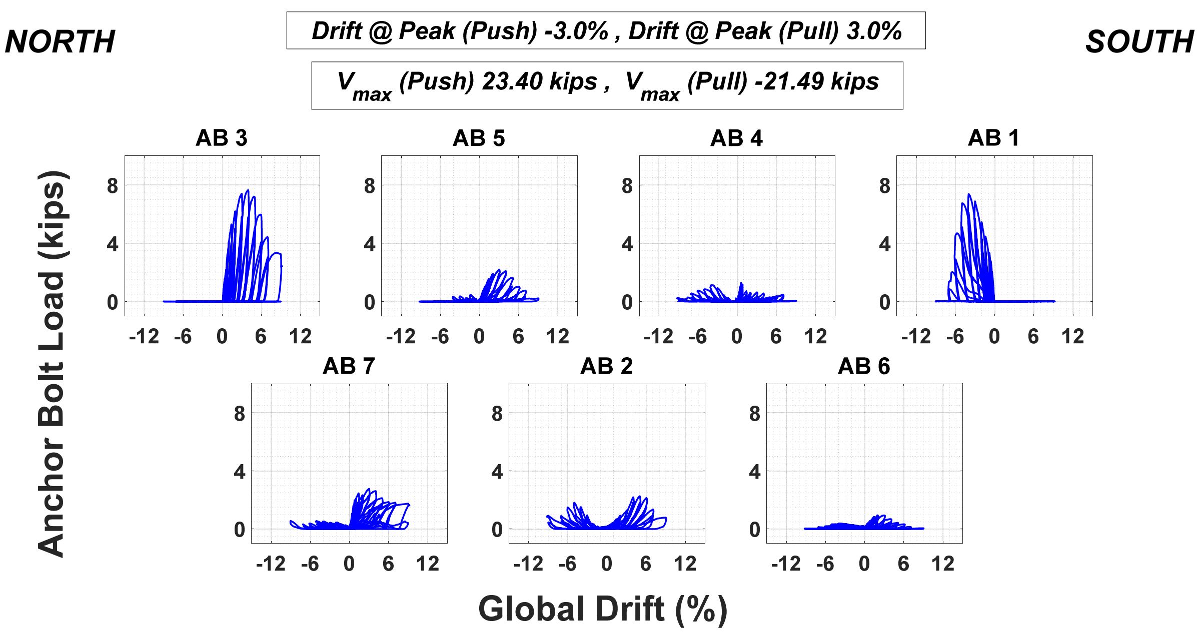


Figure C.9 Specimen A-26 anchor bolt loads versus global drift.

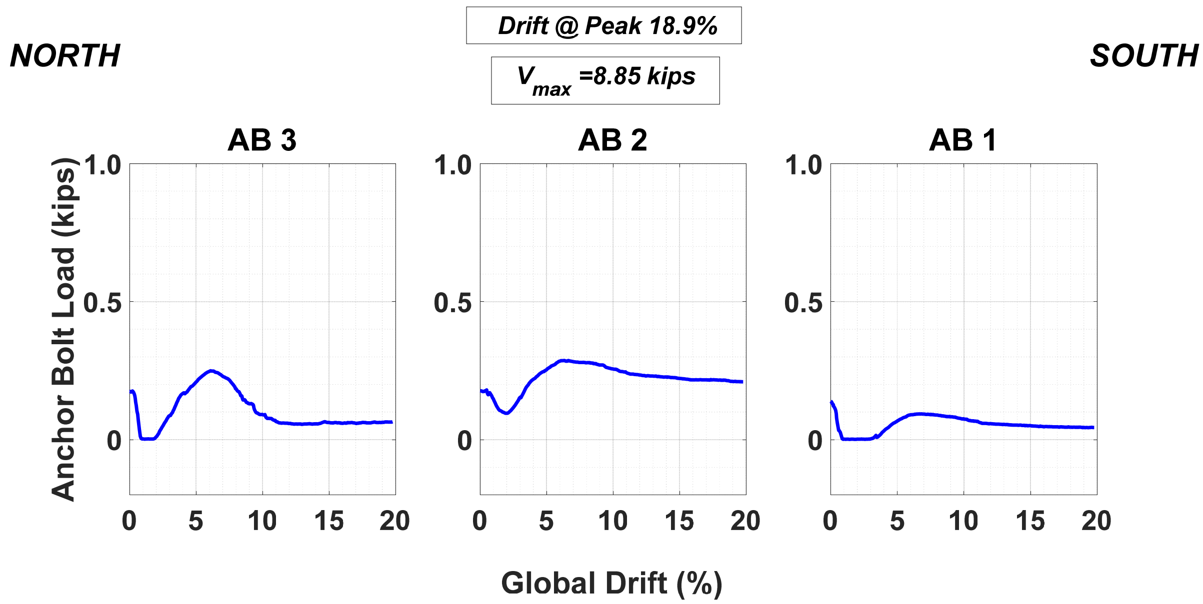


Figure C.10 Specimen A-27 anchor bolt loads versus global drift.

C.2 DIAGONAL DISTORTION MEASUREMENTS

Two pairs of linear displacement potentiometers measured the diagonal distortion of the cripple walls during testing. One pair, shown in Figure C.11 and denoted as D1 and D2, measured the distortion of the middle third of the cripple wall. These are referred to as the inner diagonal measurements. The other pair, denoted as D3 and D4, measured the distortion across the entire cripple wall. These are referred to as the outer diagonal measurements. Diagonal measurements are useful in determining the amount of shear distortion experienced by the cripple wall during testing. When coupled with the uplift measurements, LP04 and LP05, the amount of lateral displacement of the cripple wall can be resolved and compared to the measured lateral displacement. The schematic in Figure C.12 demonstrates how the resolved lateral displacements from diagonal and uplift measurements were derived. Figure C.13 shows the schematic for determining the end-of-wall uplift for each specimen.

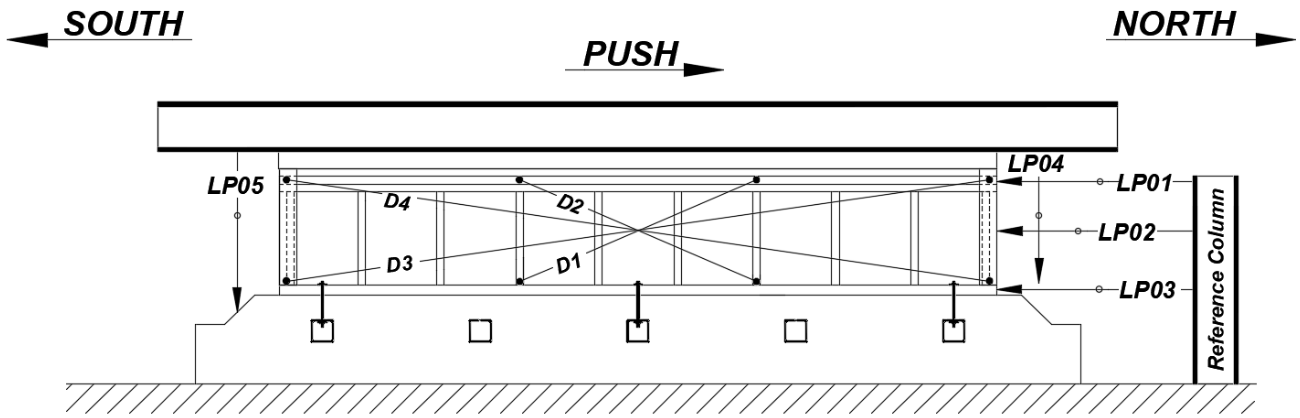


Figure C.11 Diagonal, end uplift, and lateral displacement potentiometer schematic.

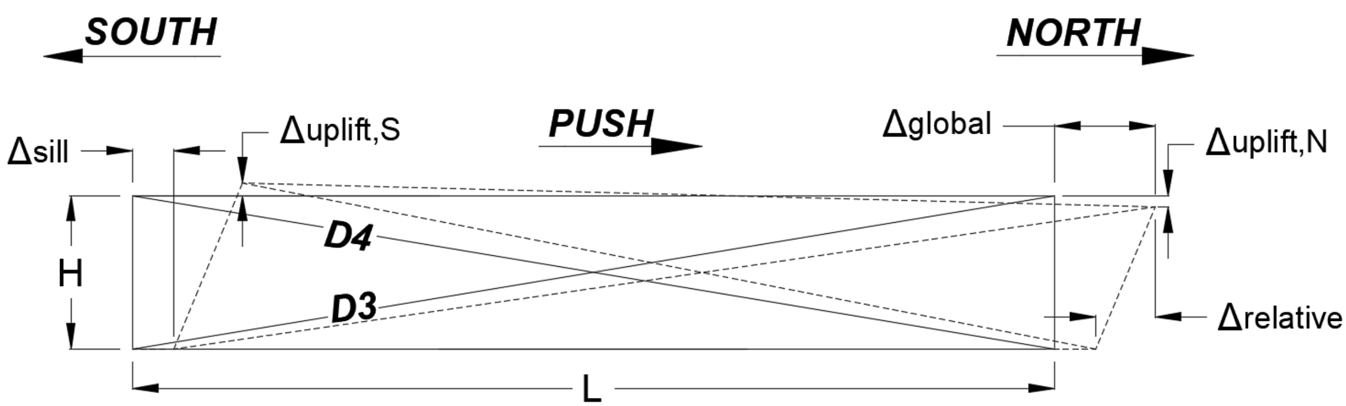


Figure C.12 Deformed cripple wall with measurements used for resolving lateral displacement from diagonal and uplift measurements.

The resolved lateral displacement from the diagonal and end uplift potentiometer measurements is as follows:

Undeformed diagonal lengths:

$$L_{D30} = L_{D40} = \sqrt{L^2 + H^2}$$

$$L_{D10} = L_{D20} = \sqrt{\left(\frac{L}{3}\right)^2 + H^2}$$

$$where, \qquad L = horizontal\ distance\ between\ D3\ and\ D4,$$
$$H = vertical\ distance\ between\ D3\ and\ D4$$

Diagonal measurement relationship

$$D1 = \ L_{D1} - L_{D10}$$
$$D2 = \ L_{D2} - L_{D20}$$
$$D3 = \ L_{D3} - L_{D30}$$
$$D4 = \ L_{D4} - L_{D40}$$

$$where, \qquad D1, D2, D3, and\ D4\ are\ the\ diagonal\ measurements$$
$$and\ L_{D1}, L_{D2}, L_{D3}, and\ L_{D4}\ are\ the\ deformed\ lengths\ of\ the\ diagonals$$

Assume the uplift is linear across the entire wall. Therefore, the uplift at locations of D1, D2, D3, and D4 measurements can be linearly interpolated:

$$\Delta_{uplift}(x) = \ \Delta_{uplift,N} + \frac{(\Delta_{uplift,S} - \Delta_{uplift,N})}{L + 2L_{end}}(x)$$

$$where\ L_{end}$$
$$= horiztonal\ distance\ from\ the\ uplift\ measurement\ to\ the\ outside\ diagonal\ measurement$$

$$For\ D1: \quad x = \frac{2L}{3} + L_{end} \ \therefore \Delta_{uplift,D1} = \ \Delta_{uplift,N} + \frac{(\Delta_{uplift,S} - \Delta_{uplift,N})}{L + 2L_{end}} * (\frac{2L}{3} + L_{end})$$

$$For\ D2: \quad x = \frac{L}{3} + L_{end} \ \therefore \Delta_{uplift,D2} = \ \Delta_{uplift,N} + \frac{(\Delta_{uplift,S} - \Delta_{uplift,N})}{L + 2L_{end}} * (\frac{L}{3} + L_{end})$$

$$For\ D3: \quad x = L + L_{end} \ \therefore \Delta_{uplift,D3} = \ \Delta_{uplift,N} + \frac{(\Delta_{uplift,S} - \Delta_{uplift,N})}{L + 2L_{end}} * (\ L + L_{end})$$

$$For\ D4: \quad x = L_{end} \ \therefore \Delta_{uplift,D4} = \ \Delta_{uplift,N} + \frac{(\Delta_{uplift,S} - \Delta_{uplift,N})}{L + 2L_{end}} * (\ L_{end})$$

$$where\ \Delta_{uplift,N}\ is\ measured\ from\ LP04\ and\ \Delta_{uplift,S}\ are\ measured\ from\ LP05$$

Deformed diagonal lengths (sample calculation for D1)

$$L_{D1} = \ \sqrt{(\frac{L}{3} - \Delta_{relative})^2 + (H + \Delta_{uplift,D1})^2}$$

$$L_{D2} = \ \sqrt{(\frac{L}{3} + \Delta_{relative})^2 + (H + \Delta_{uplift,D2})^2}$$

$$L_{D3} = \sqrt{(L - \Delta_{relative})^2 + (H + \Delta_{uplift,D3})^2}$$

$$L_{D4} = \sqrt{(L + \Delta_{relative})^2 + (H + \Delta_{uplift,D4})^2}$$

$$where\ \Delta_{relative}\ is\ positive\ in\ the\ push\ direction\ and\ negative\ in\ the\ pull\ direction$$

Vertical component of uplift measurements

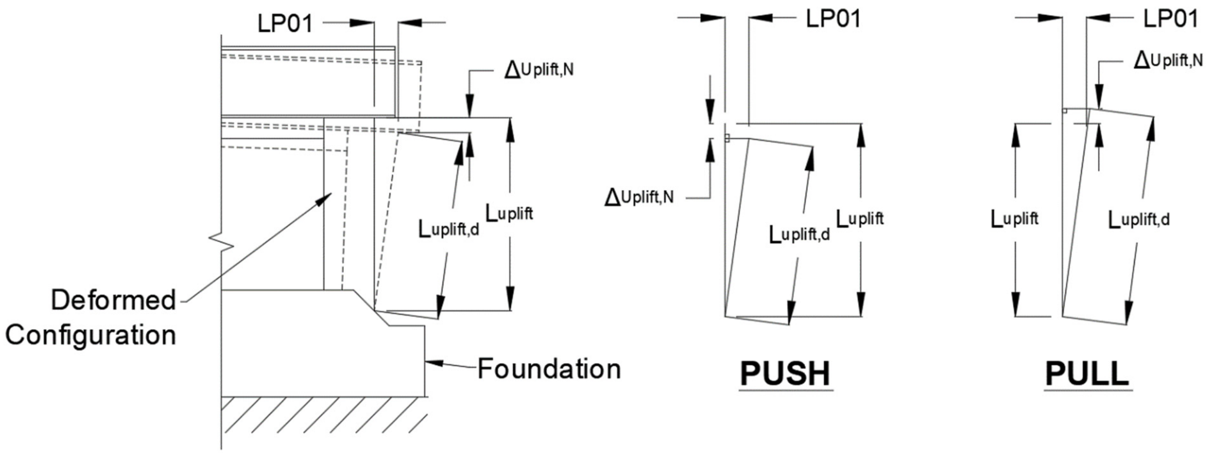


Figure C.13 Schematic for resolving end of wall uplift.

$Let,\quad L_{uplift} = length\ of\ uplift\ measurement\ string,\ L_{uplift,d} = deformed\ length\ of\ uplift\ measurement\ string$

Push loading

$$L_{uplift,d} = L_{uplift} + LP04$$

$$L_{uplift,d}^2 = \left(L_{uplift} - \Delta_{uplift,S}\right)^2 + LP01^2$$

$$\Rightarrow \left(L_{uplift} + LP04\right)^2 = \left(L_{uplift} - \Delta_{uplift,S}\right)^2 + LP01^2$$

$$\Rightarrow \left(L_{uplift} - \Delta_{uplift,S}\right)^2 = \left(L_{uplift} + LP04\right)^2 - LP01^2$$

$$\therefore\ \Delta_{uplift,S} = L_{uplift} - \sqrt{\left(L_{uplift} + LP04\right)^2 - LP01^2}$$

$$\therefore\ \Delta_{uplift,N} = L_{uplift} - \sqrt{\left(L_{uplift} + LP05\right)^2 - LP01^2}$$

Pull loading

$$L_{uplift,d} = L_{uplift} + LP04$$

$$L^2_{uplift,d} = \left(L_{uplift} + \Delta_{uplift,S}\right)^2 + LP01^2$$

$$\Rightarrow \left(L_{uplift} + LP04\right)^2 = \left(L_{uplift} + \Delta_{uplift,S}\right)^2 + LP01^2$$

$$\Rightarrow \left(L_{uplift} + \Delta_{uplift,S}\right)^2 = \left(L_{uplift} + LP04\right)^2 - LP01^2$$

$$\therefore\ \Delta_{uplift,S} = \sqrt{\left(L_{uplift} + LP04\right)^2 - LP01^2} - L_{uplift}$$

$$\therefore\ \Delta_{uplift,N} = \sqrt{\left(L_{uplift} + LP05\right)^2 - LP01^2} - L_{uplift}$$

Solving for relative displacements as a function of uplift and diagonal measurements

$$D1 = L_{D1} - L_{D10} \Rightarrow D1 = \sqrt{\left(\frac{L}{3} + \Delta_{relative}\right)^2 + \left(H + \Delta_{uplift,D1}\right)^2} - \sqrt{\left(\frac{L}{3}\right)^2 + H^2}$$

$$\Rightarrow D1 + \sqrt{\left(\frac{L}{3}\right)^2 + H^2} = \sqrt{\left(\frac{L}{3} + \Delta_{relative}\right)^2 + \left(H + \Delta_{uplift,D1}\right)^2}$$

$$\Rightarrow D1^2 + 2D1\sqrt{\left(\frac{L}{3}\right)^2 + H^2} + \left(\frac{L}{3}\right)^2 + H^2 = \left(\frac{L}{3} + \Delta_{relative}\right)^2 + \left(H + \Delta_{uplift,D1}\right)^2$$

$$\Rightarrow D1^2 + 2D1\sqrt{\left(\frac{L}{3}\right)^2 + H^2} + \left(\frac{L}{3}\right)^2 + H^2 - \left(H + \Delta_{uplift,D1}\right)^2 = \left(\frac{L}{3} + \Delta_{relative}\right)^2$$

$$\Rightarrow \sqrt{D1^2 + 2D1\sqrt{\left(\frac{L}{3}\right)^2 + H^2} + \left(\frac{L}{3}\right)^2 + H^2 - \left(H + \Delta_{uplift,D1}\right)^2} = \frac{L}{3} + \Delta_{relative}$$

Resolved lateral displacements as a function of the uplift and diagonal measurements

$$\therefore\ \Delta_{relative} = \sqrt{D1^2 + 2D1\sqrt{\left(\frac{L}{3}\right)^2 + H^2} + \left(\frac{L}{3}\right)^2 + H^2 - \left(H + \Delta_{uplift,D1}\right)^2} - \frac{L}{3} \quad for\ D1$$

$$\therefore\ \Delta_{relative} = \frac{L}{3} - \sqrt{D2^2 + 2D2\sqrt{\left(\frac{L}{3}\right)^2 + H^2} + \left(\frac{L}{3}\right)^2 + H^2 - \left(H + \Delta_{uplift,D2}\right)^2} \quad for\ D2$$

$$\therefore\ \Delta_{relative} = \sqrt{D3^2 + 2D3\sqrt{L^2 + H^2} + L^2 + H^2 - \left(H + \Delta_{uplift,D3}\right)^2} - L \quad for\ D3$$

$$\therefore\ \Delta_{relative} = L - \sqrt{D2^2 + 2D2\sqrt{L^2 + H^2} + L^2 + H^2 - \left(H + \Delta_{uplift,D4}\right)^2} \quad for\ D4$$

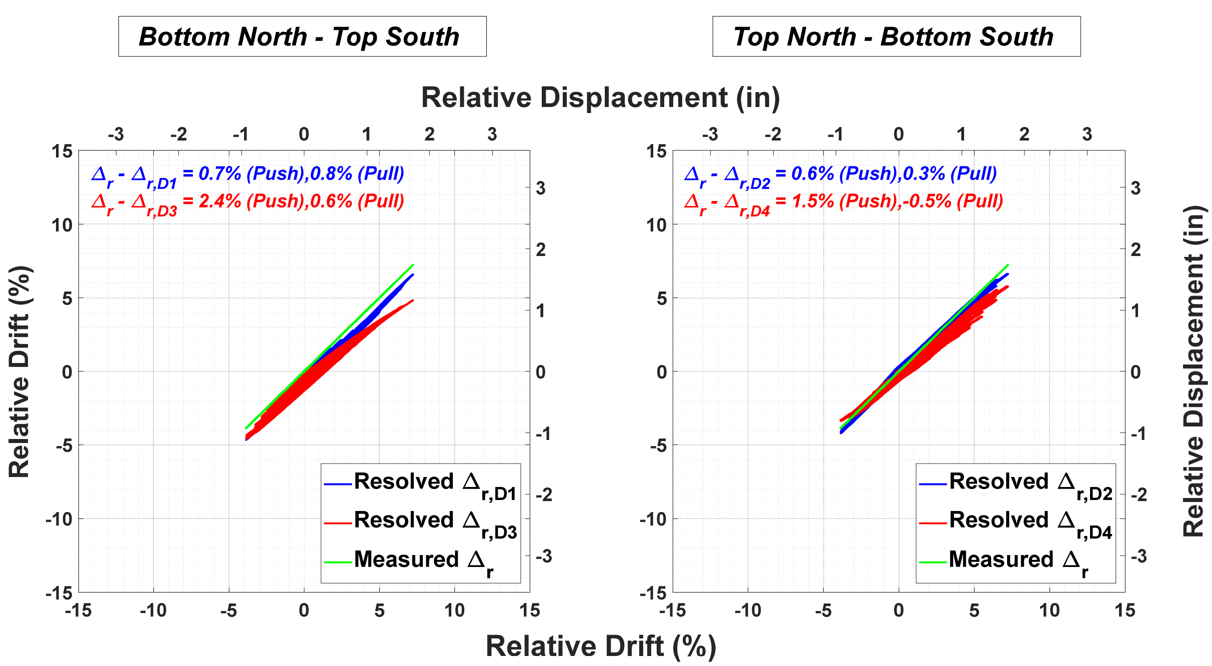


Figure C.14 **Specimen A-15 resolved relative drift from diagonal measurements in one direction versus measured relative drift.**

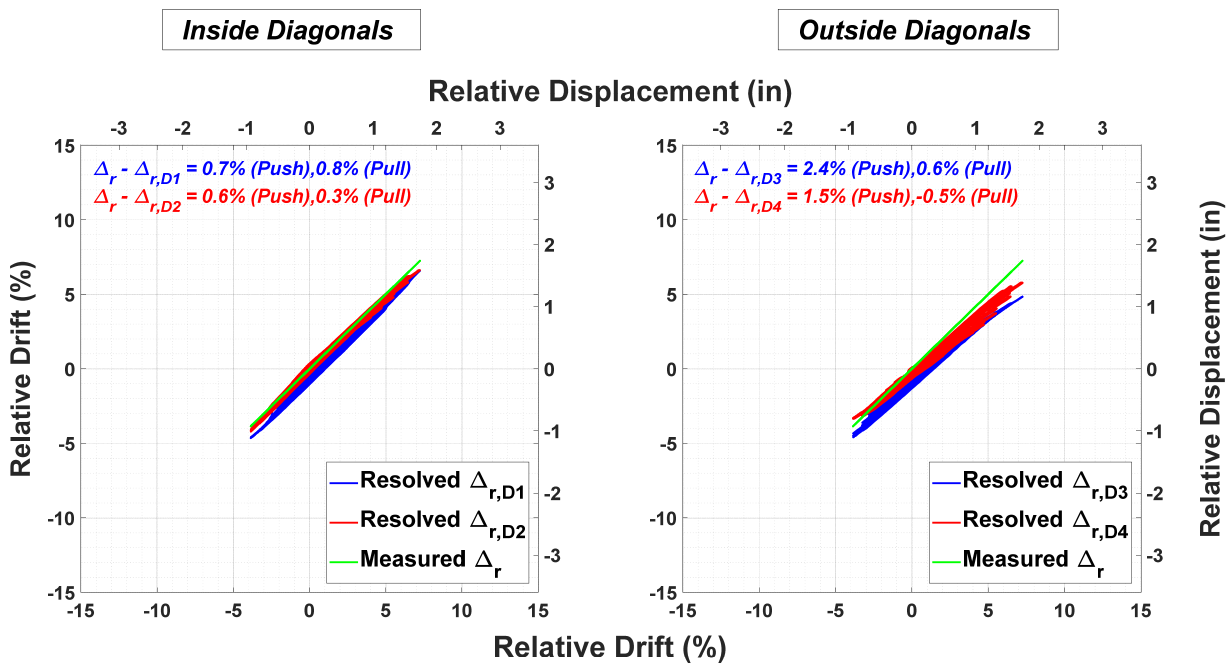


Figure C.15 **Specimen A-15 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.**

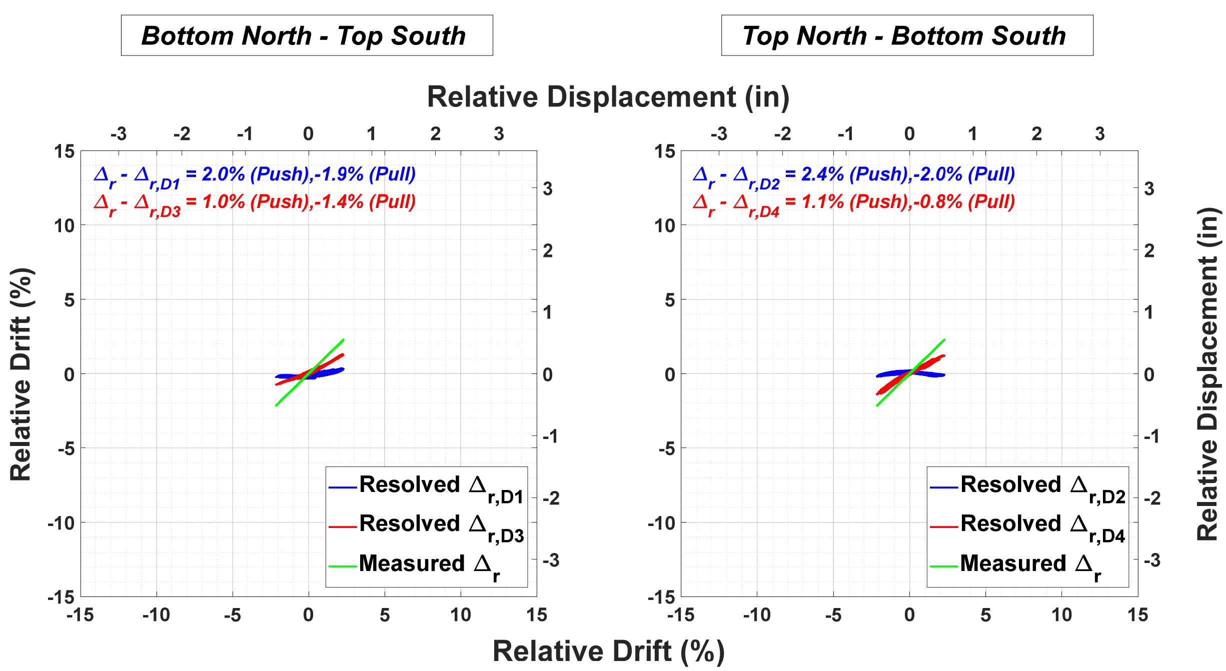


Figure C.16 **Specimen A-16 resolved relative drift from diagonal measurements in one direction versus measured relative drift.**

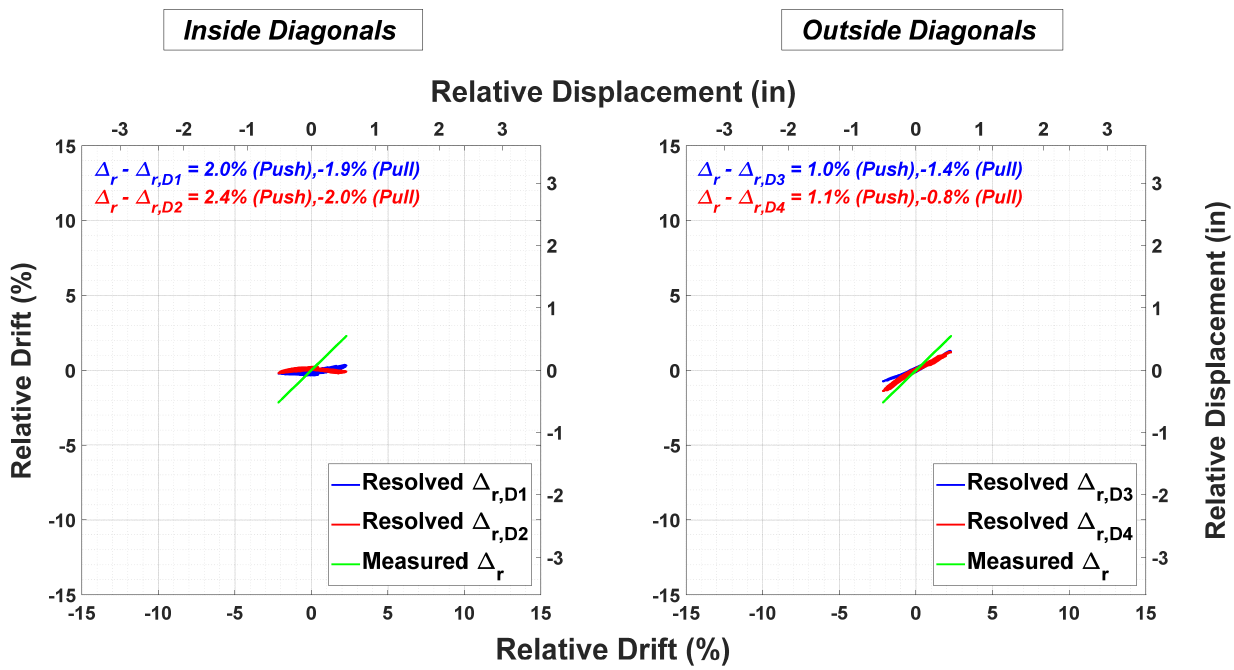


Figure C.17 Specimen A-16 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.

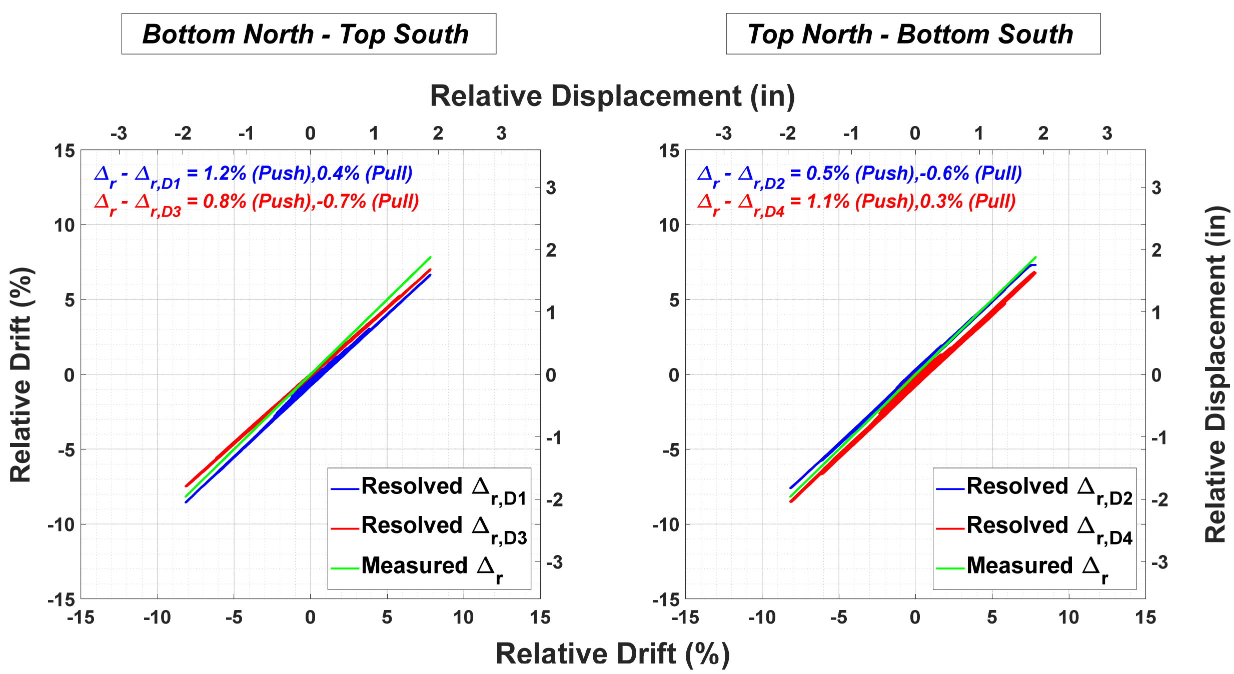


Figure C.18 Specimen A-17 resolved relative drift from diagonal measurements in one direction versus measured relative drift.

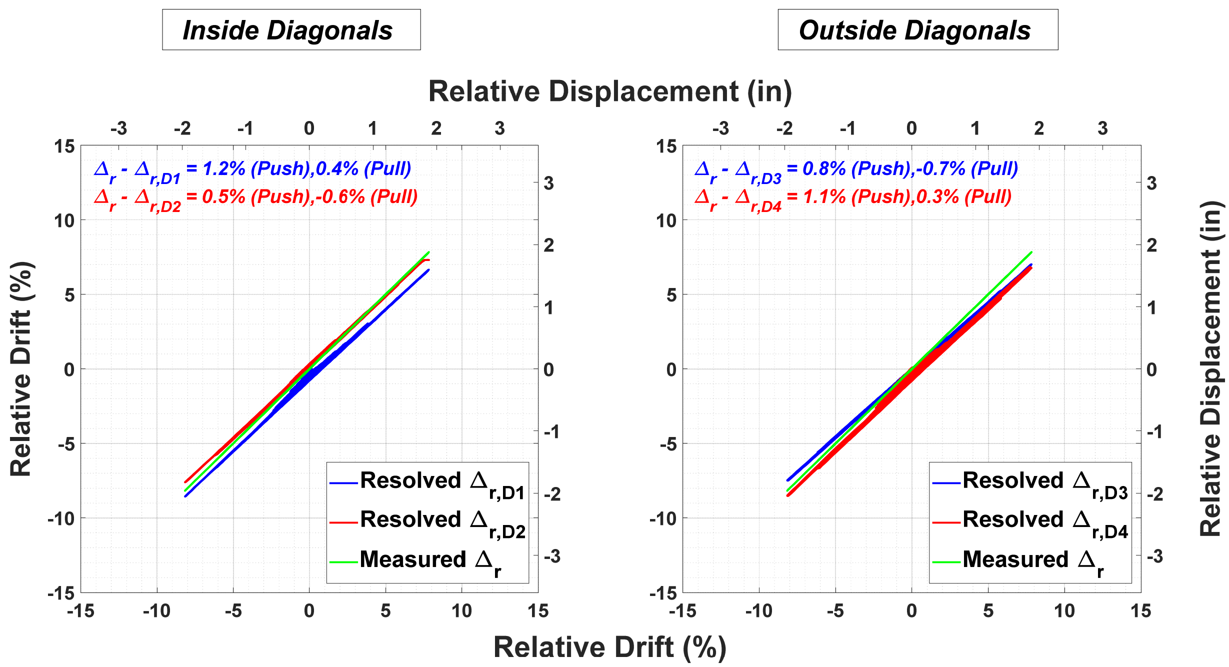


Figure C.19 Specimen A-17 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.

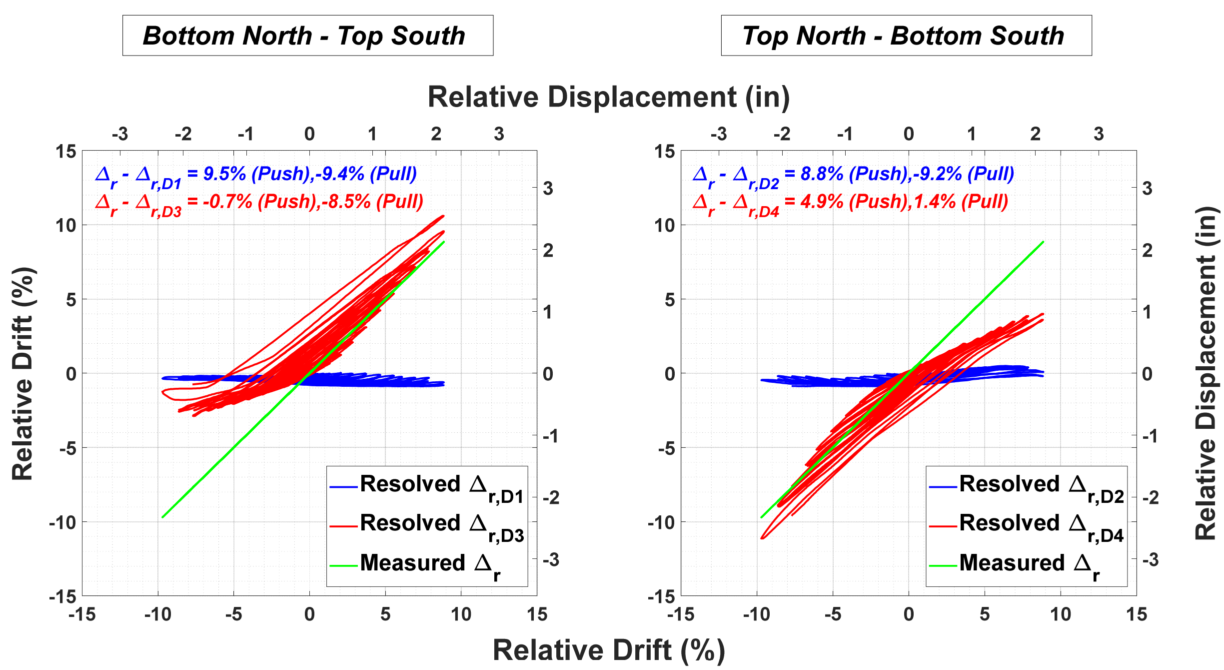


Figure C.20 Specimen A-18 resolved relative drift from diagonal measurements in one direction versus measured relative drift.

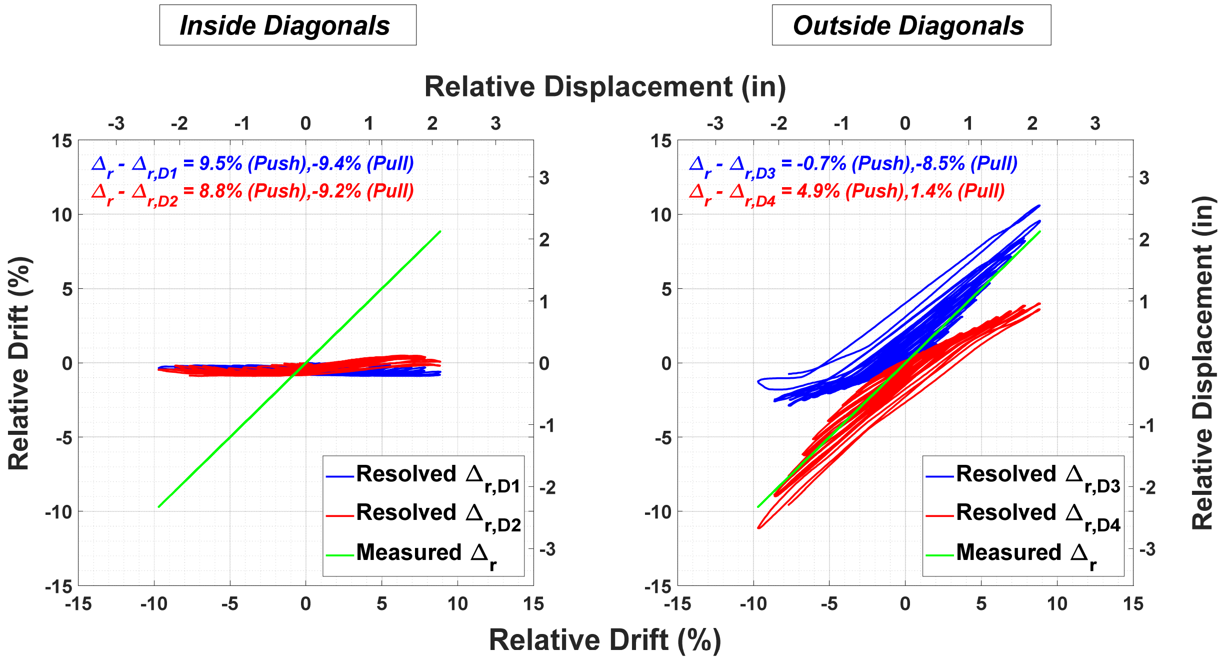


Figure C.21 Specimen A-18 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.

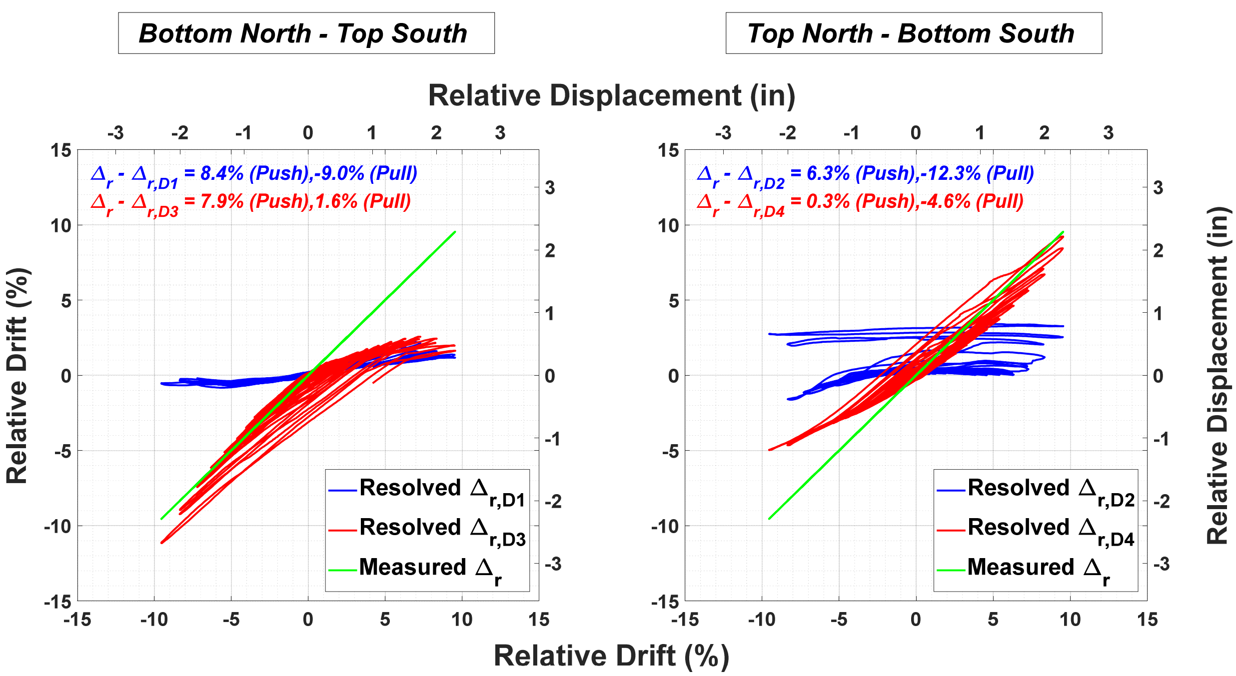


Figure C.22 Specimen A-19 resolved relative drift from diagonal measurements in one direction versus measured relative drift.

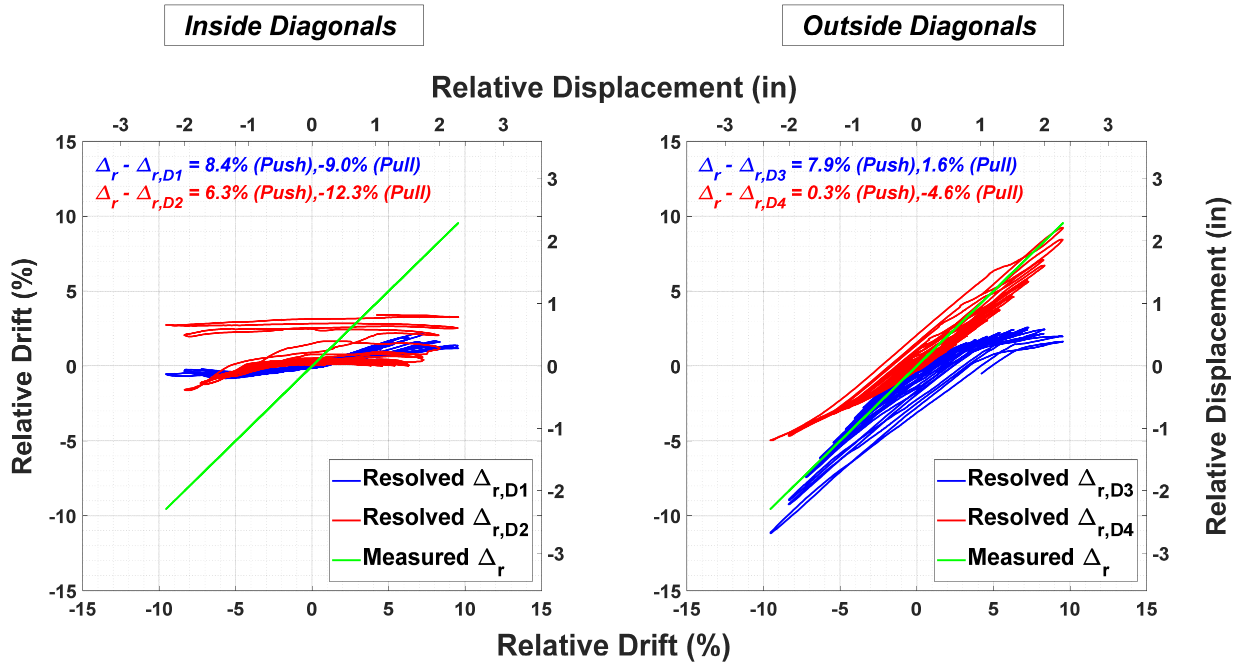


Figure C.23 Specimen A-19 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.

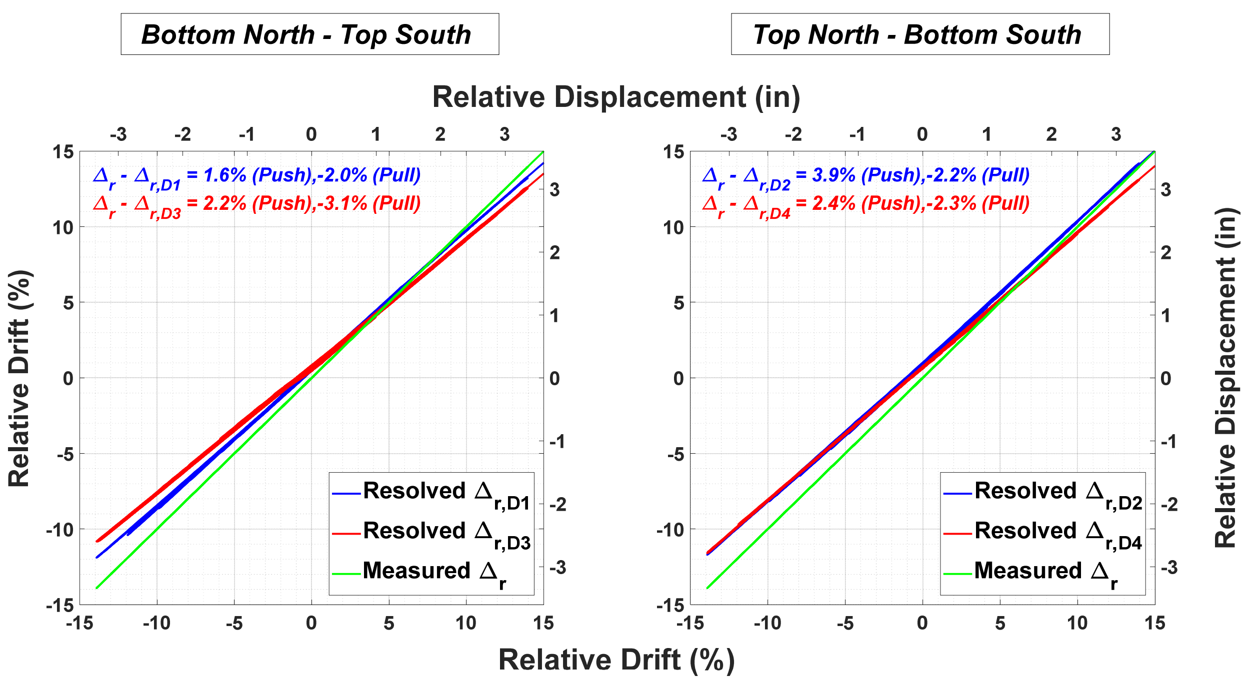


Figure C.24 Specimen A-20 resolved relative drift from diagonal measurements in one direction versus measured relative drift.

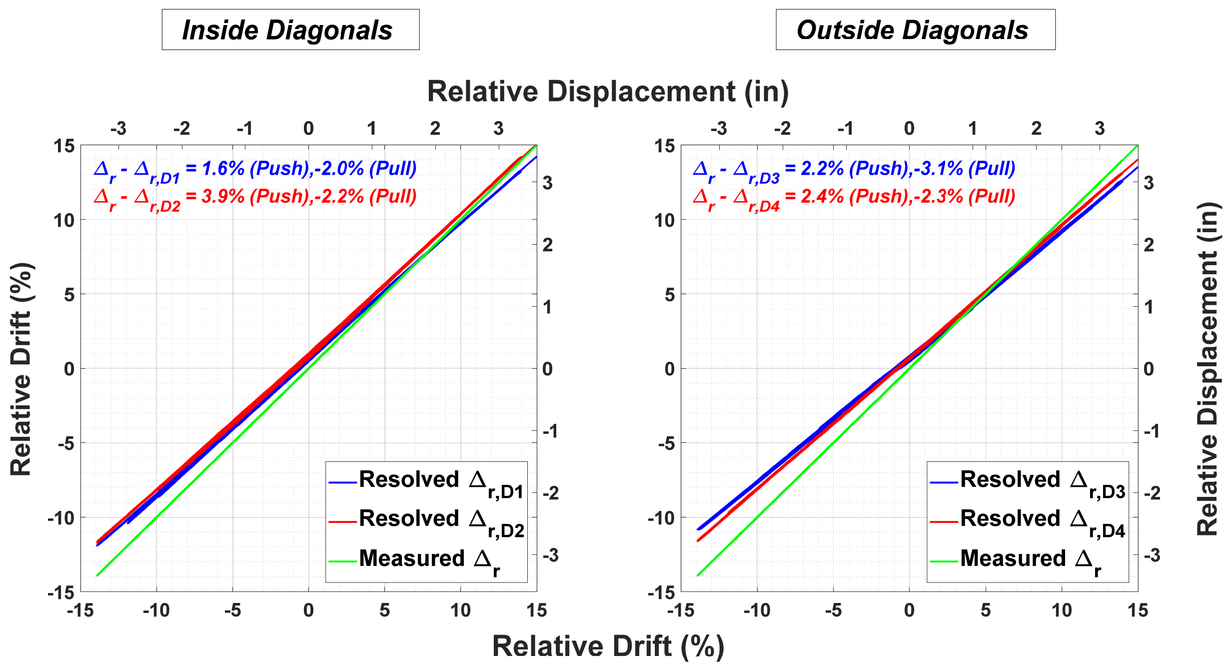


Figure C.25 **Specimen A-20 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.**

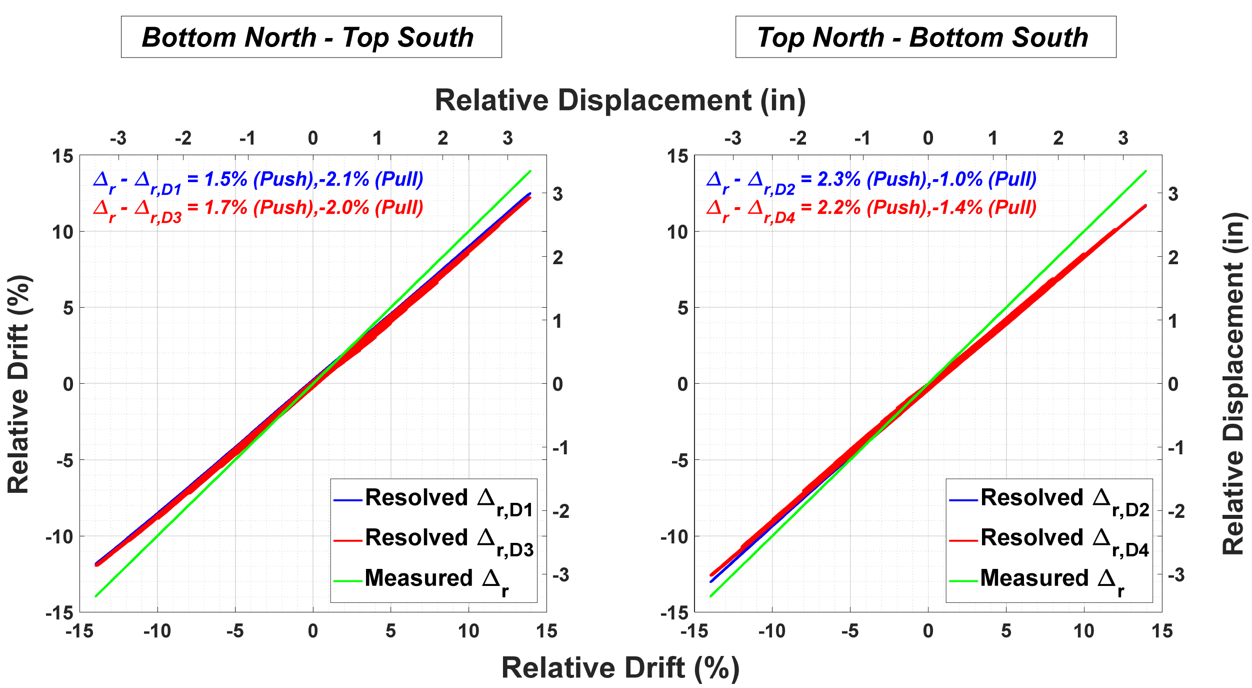


Figure C.26 **Specimen A-21 resolved relative drift from diagonal measurements in one direction versus measured relative drift.**

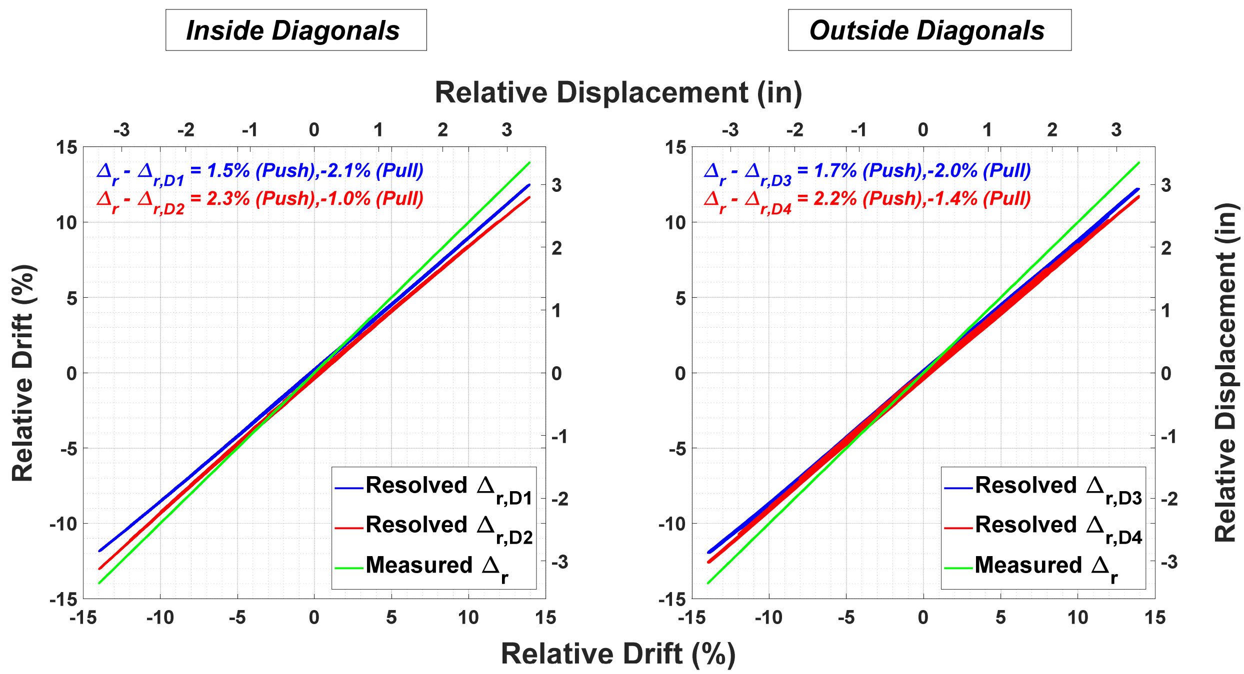


Figure C.27 Specimen A-21 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.

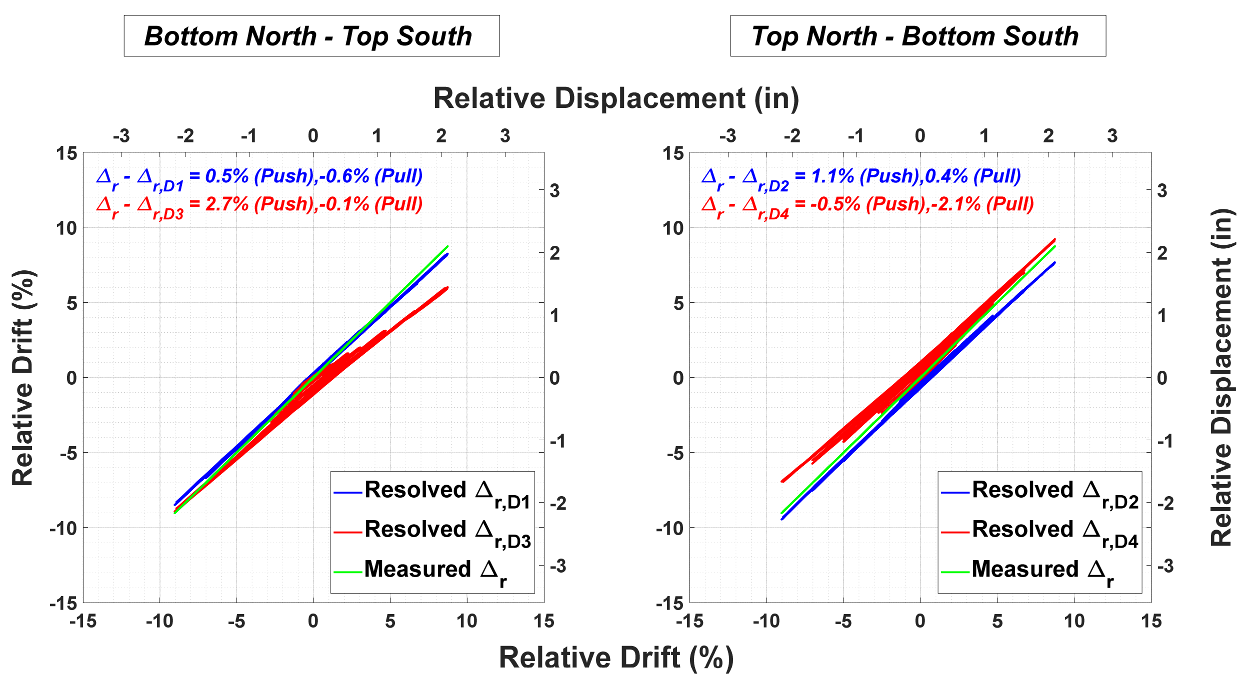


Figure C.28 Specimen A-22 resolved relative drift from diagonal measurements in one direction versus measured relative drift.

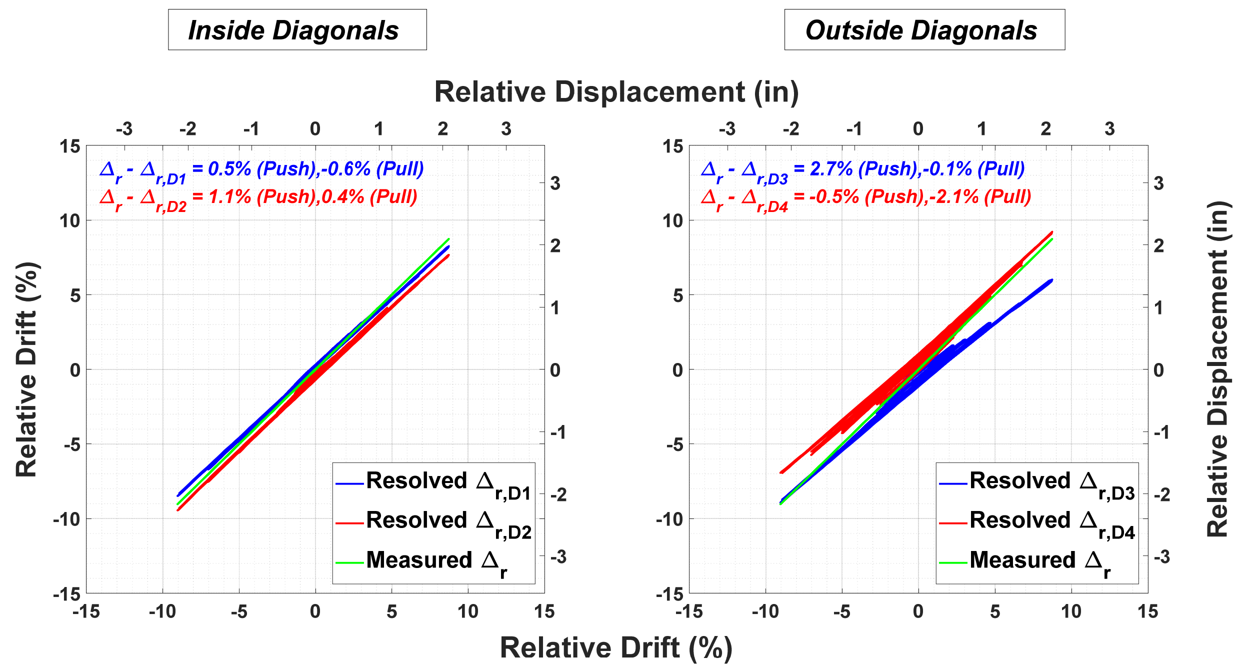


Figure C.29 Specimen A-22 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.

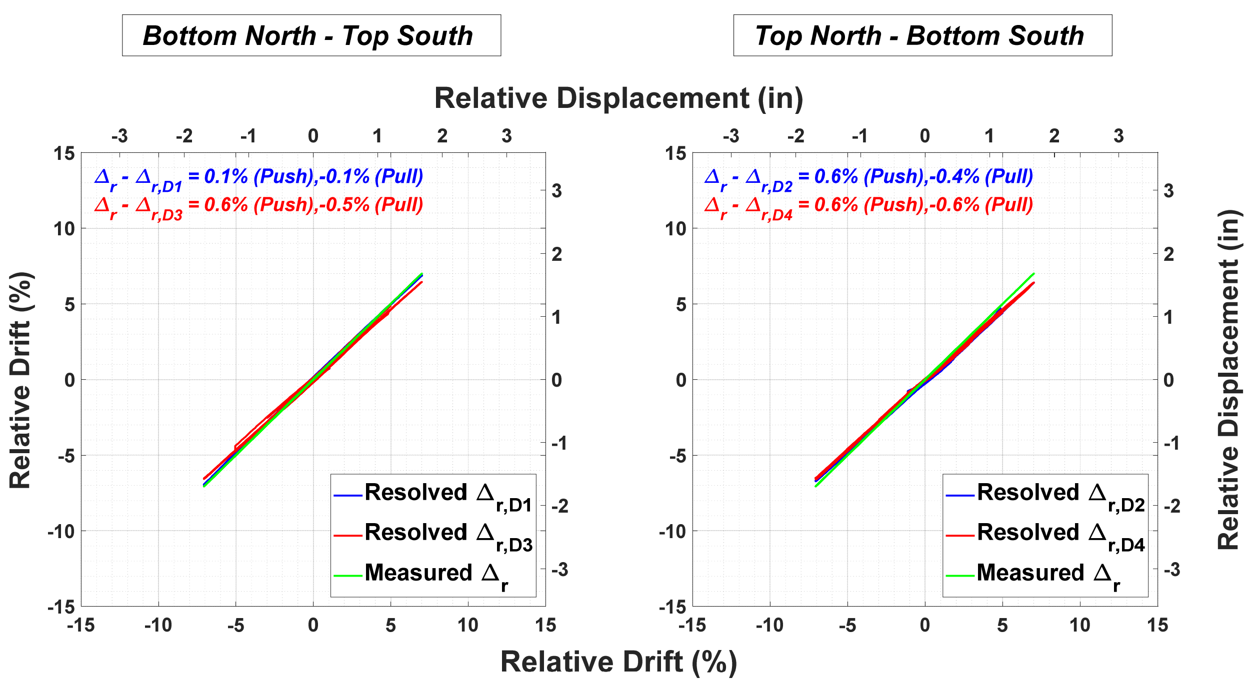


Figure C.30 Specimen A-25 resolved relative drift from diagonal measurements in one direction versus measured relative drift.

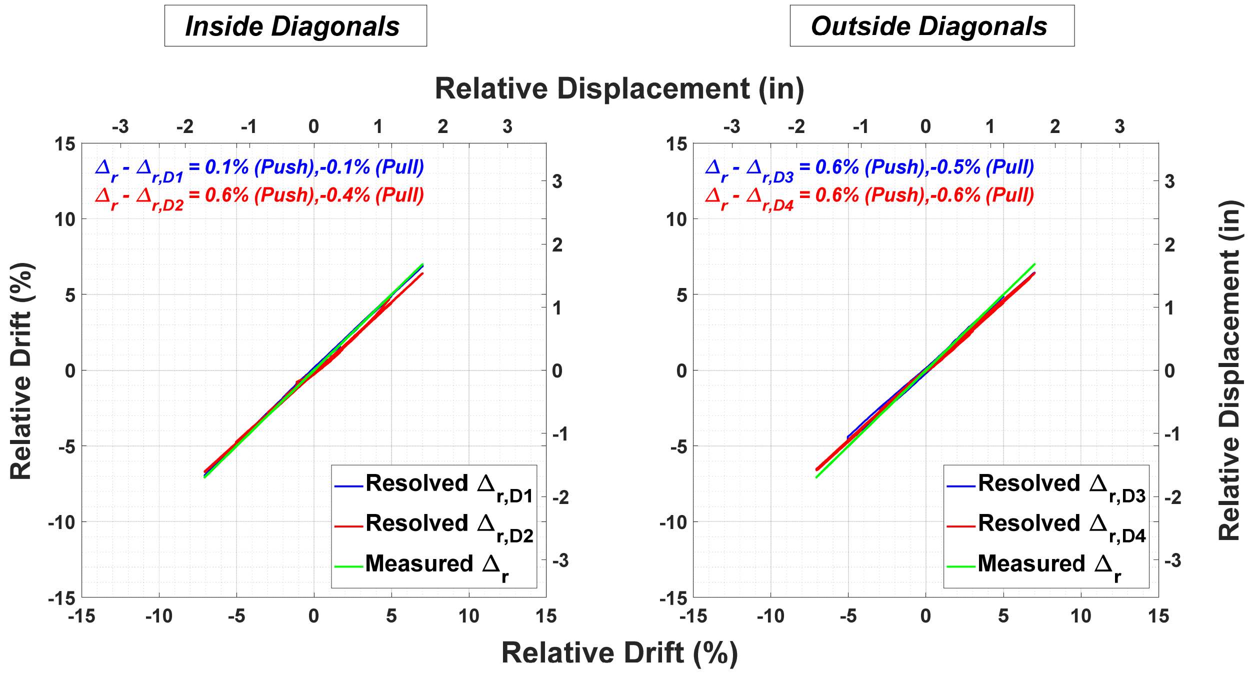


Figure C.31 Specimen A-25 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.

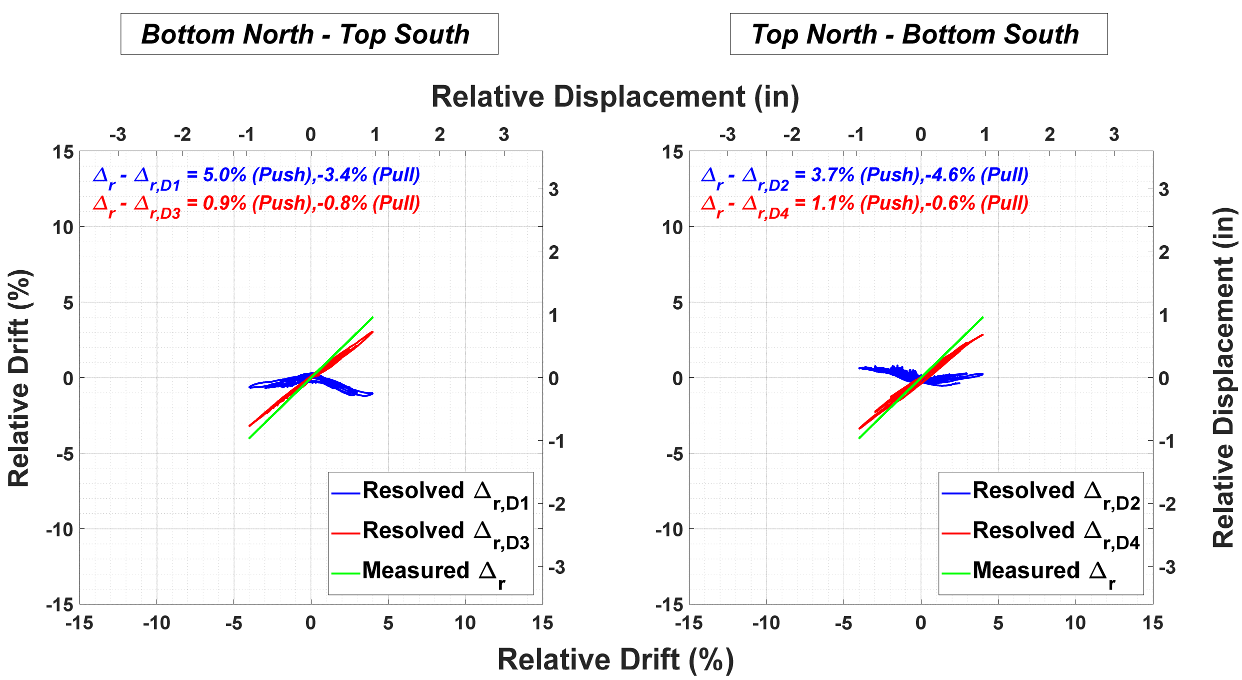


Figure C.32 Specimen A-26 resolved relative drift from diagonal measurements in one direction versus measured relative drift.

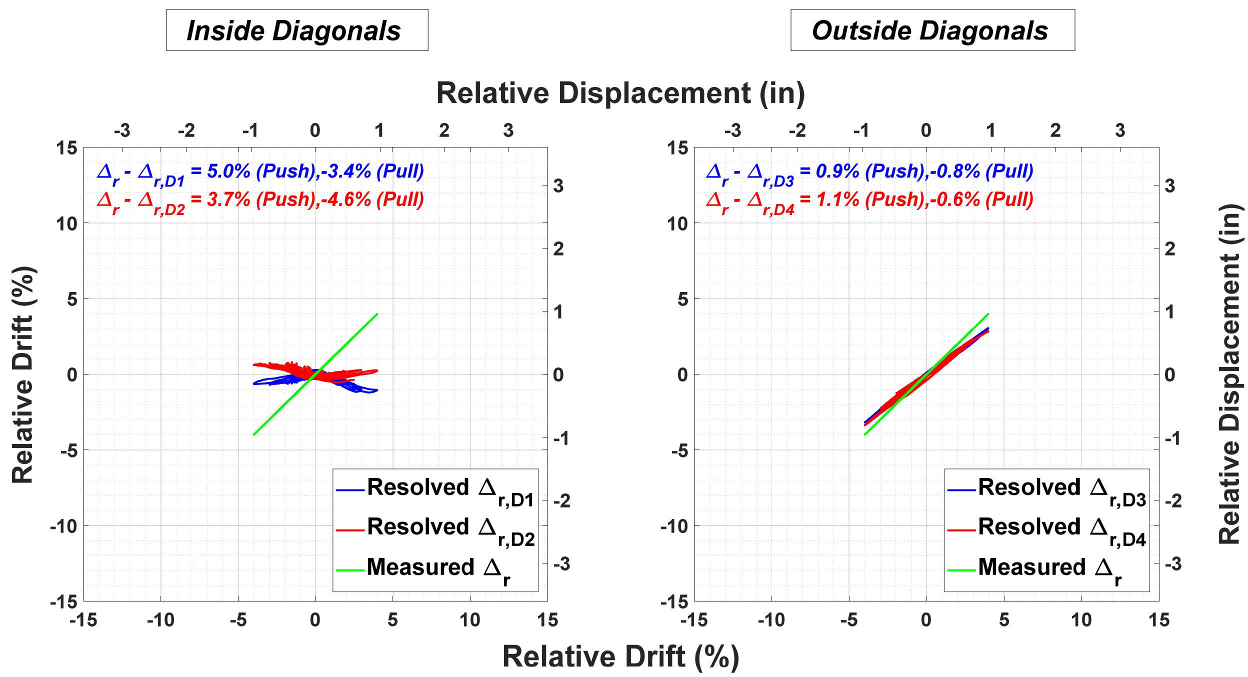


Figure C.33 Specimen A-26 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.

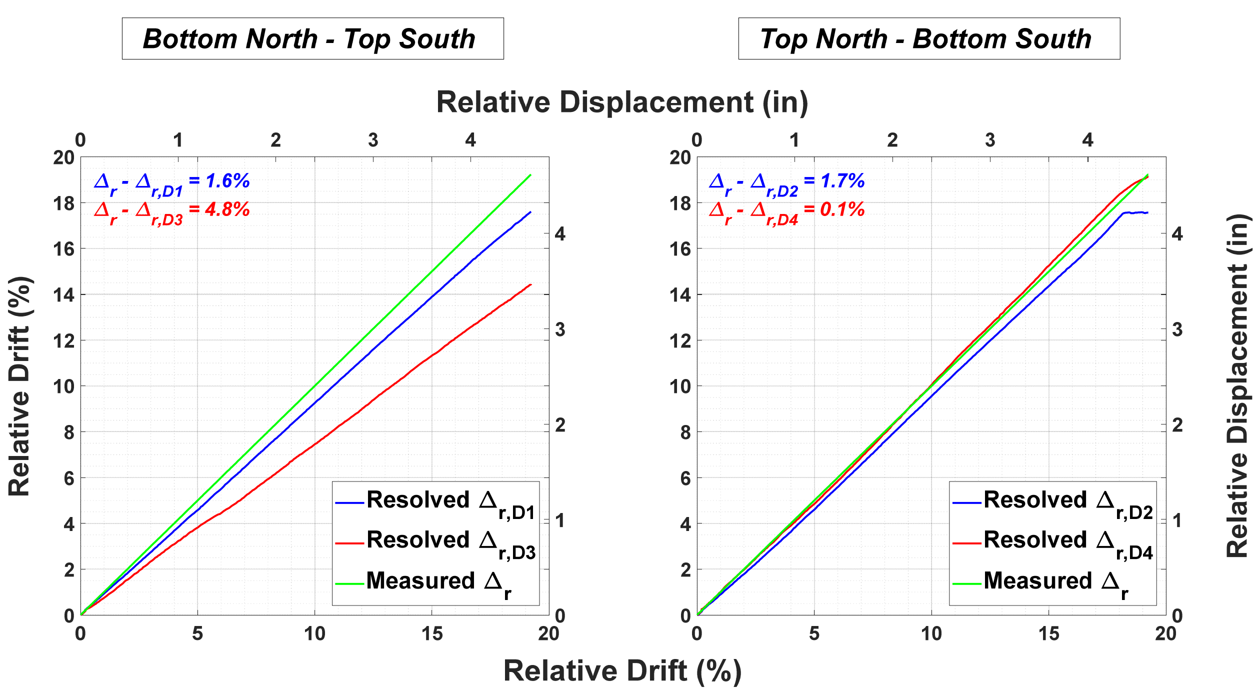


Figure C.34 Specimen A-27 resolved relative drift from diagonal measurements in one direction versus measured relative drift.

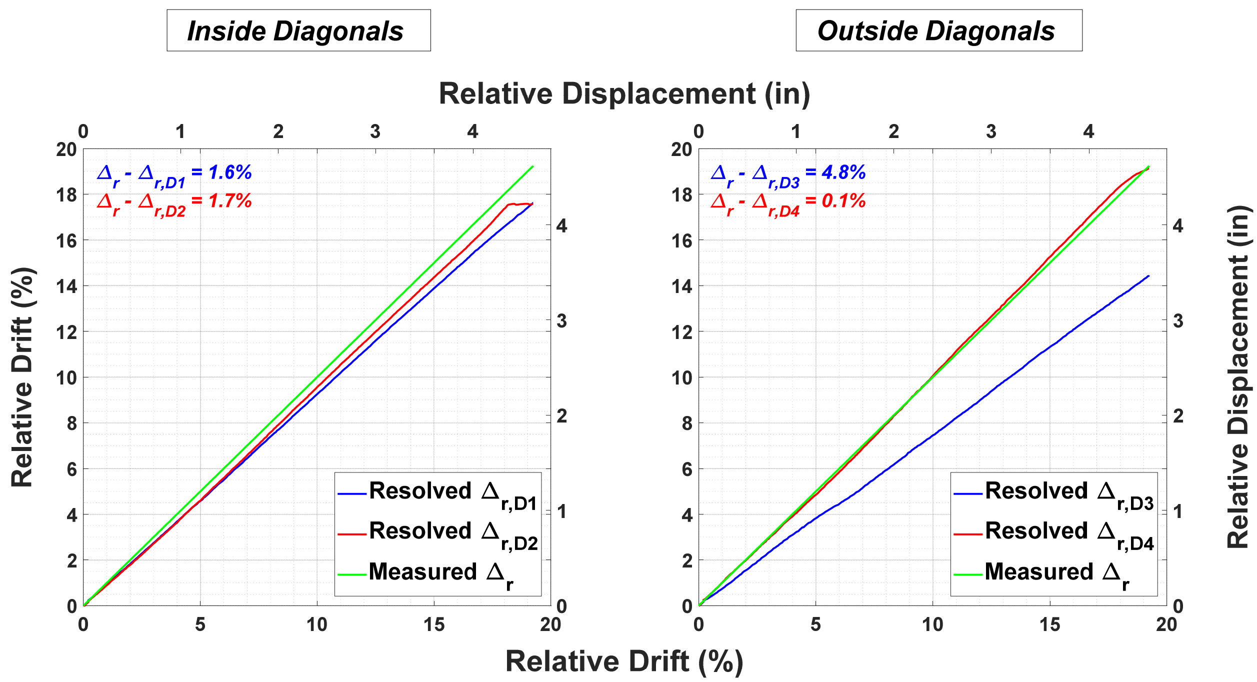


Figure C.35 **Specimen A-27 resolved relative drift from diagonal measurements (outside and inside diagonals) versus measured relative drift.**

C.3 UPLIFT MEASUREMENTS

Two linear potentiometers were used to measure the uplift at both ends of the cripple wall. These potentiometers were attached to the foundation and the steel load transfer beam. The calculations for determining the uplift of the cripple walls are shown in the previous section as the uplift measurements were factored into calculating the resolved relative displacement from the diagonal measurements.

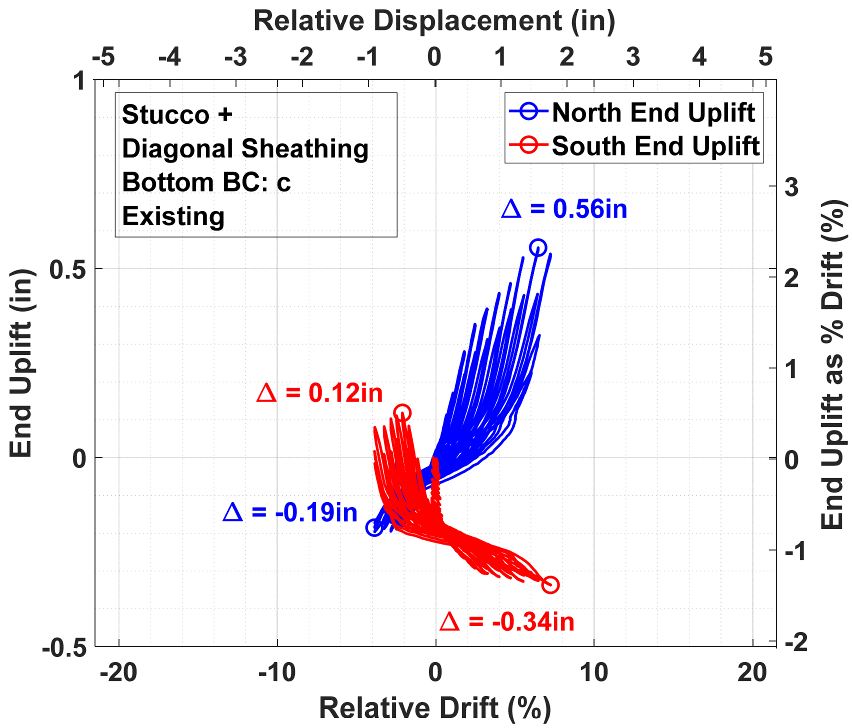


Figure C.36 Specimen A-15 end uplift versus *relative* drift.

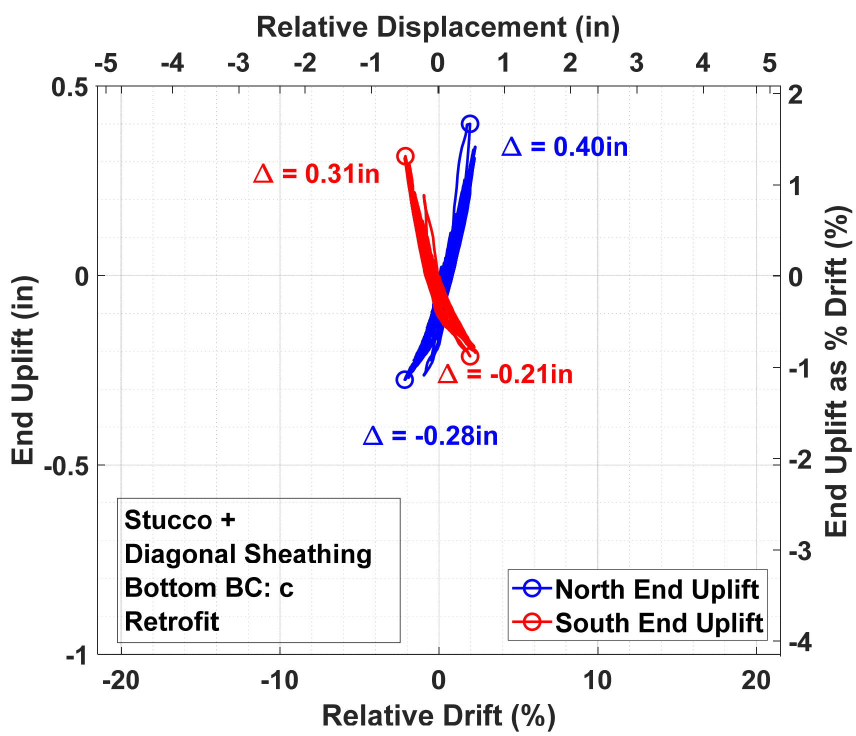


Figure C.37 Specimen A-16 end uplift versus *relative* drift.

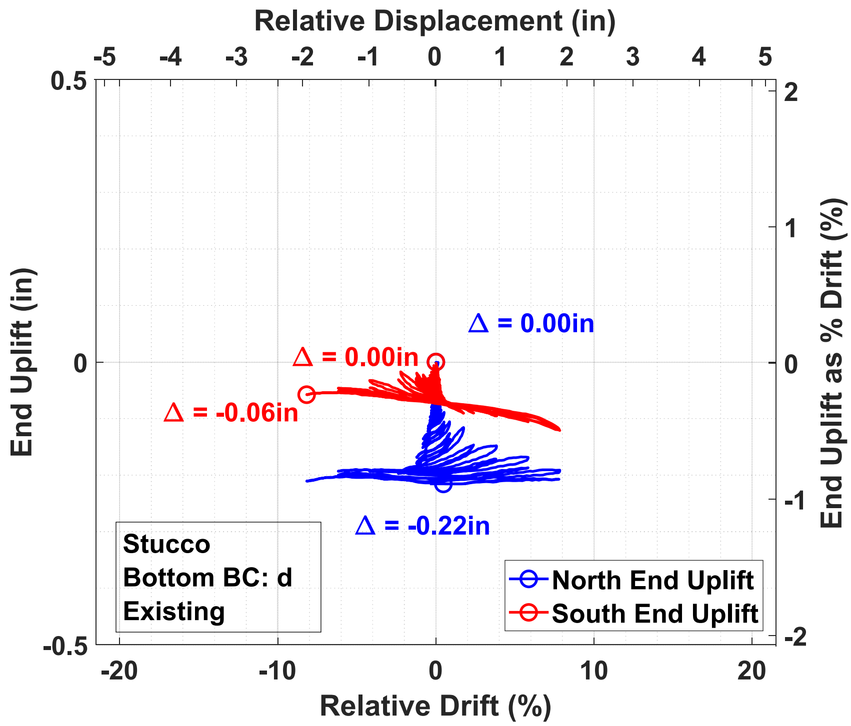


Figure C.38 Specimen A-17 end uplift versus *relative* drift.

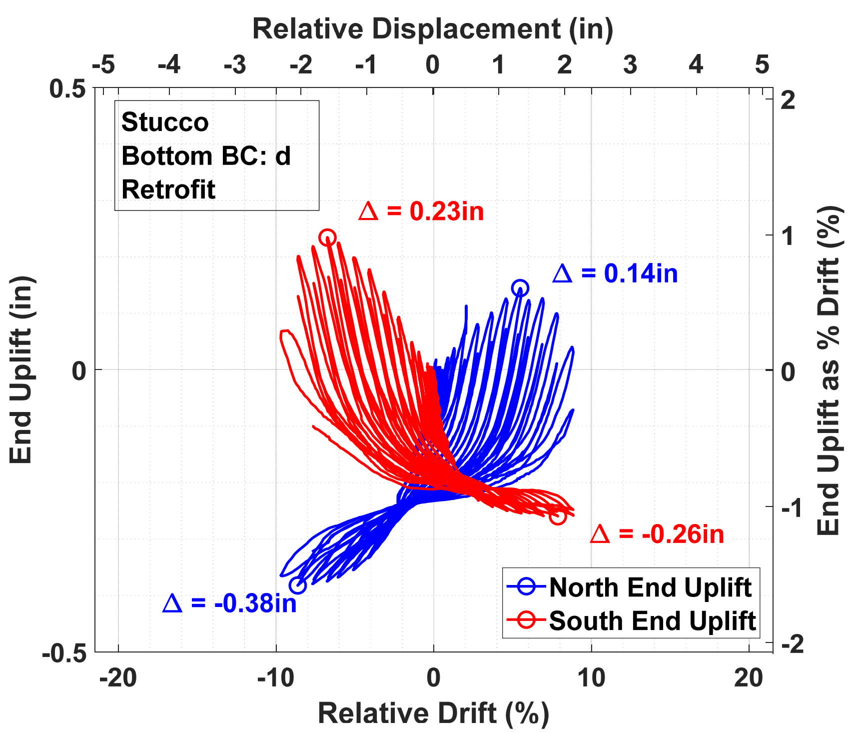


Figure C.39 Specimen A-18 end uplift versus *relative* drift.

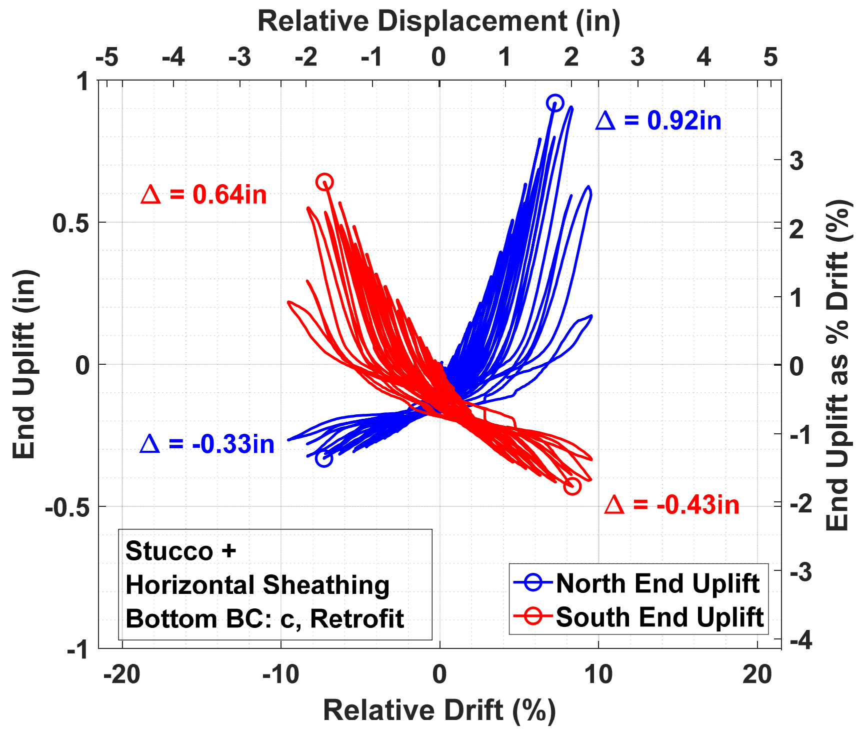


Figure C.40 Specimen A-19 end uplift versus *relative* drift.

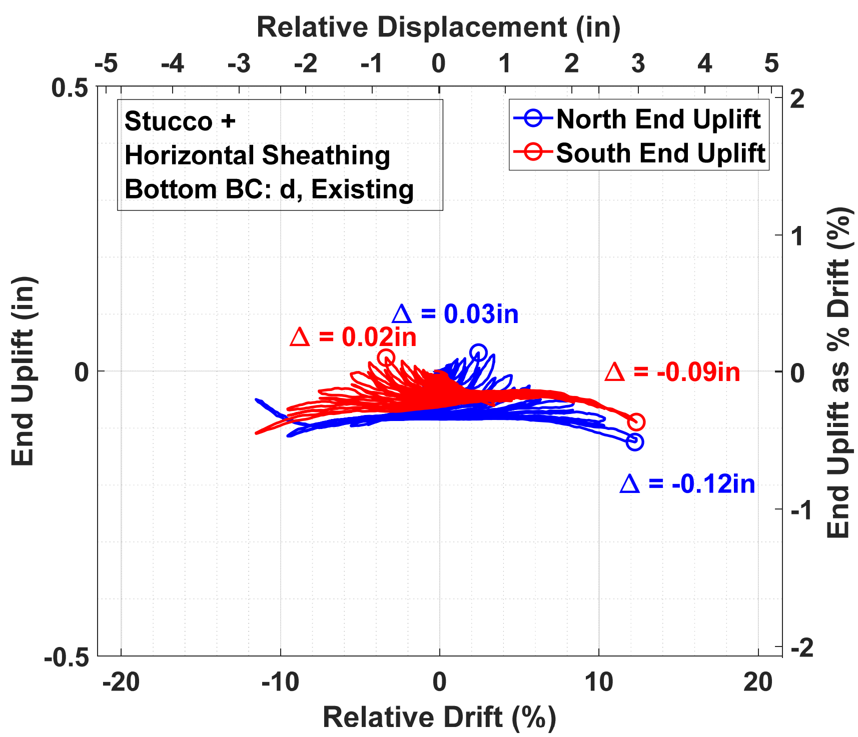


Figure C.41 Specimen A-20 end uplift versus *relative* drift.

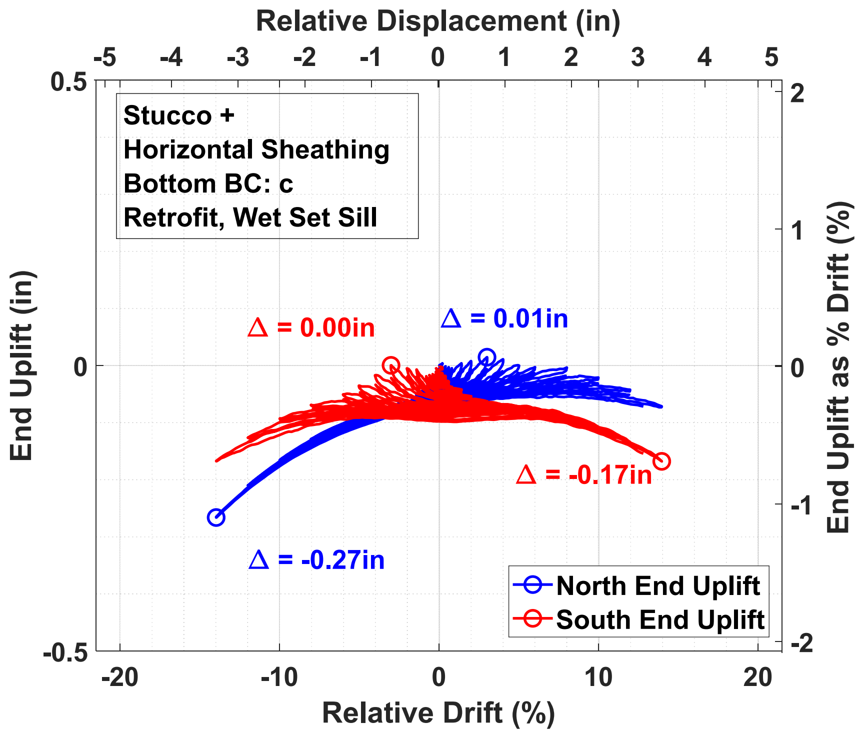


Figure C.42 Specimen A-21 end uplift versus *relative* drift.

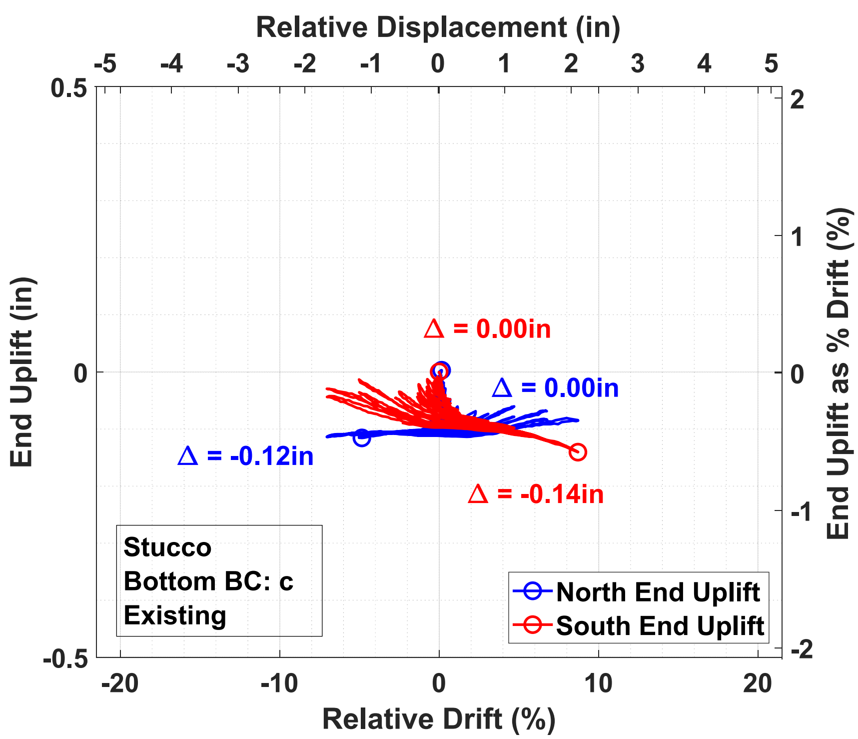


Figure C.43 Specimen A-22 end uplift versus *relative* drift.

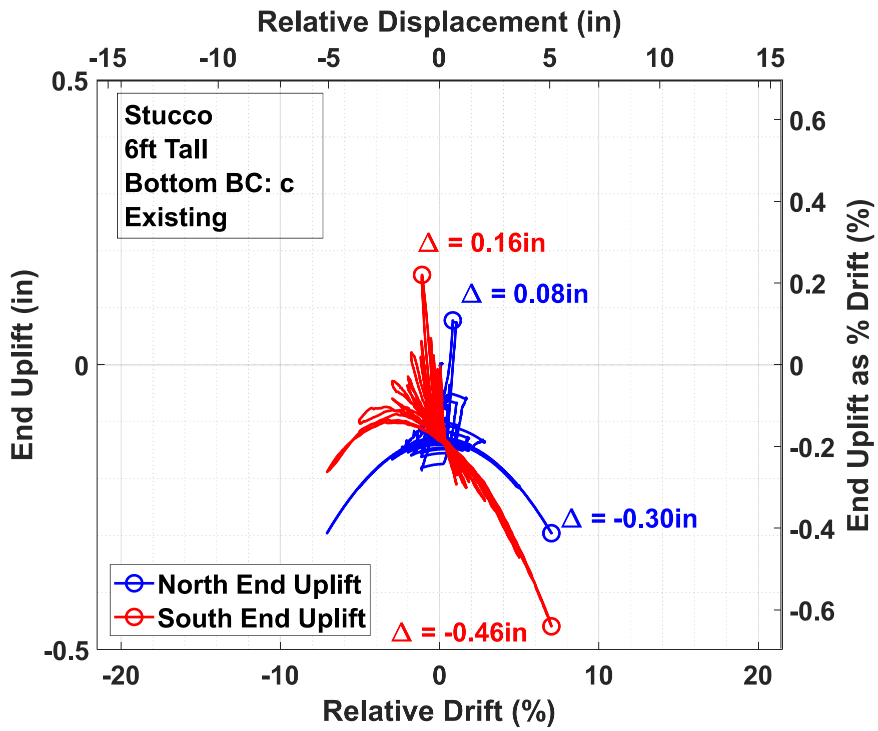


Figure C.44 Specimen A-25 end uplift versus *relative* drift.

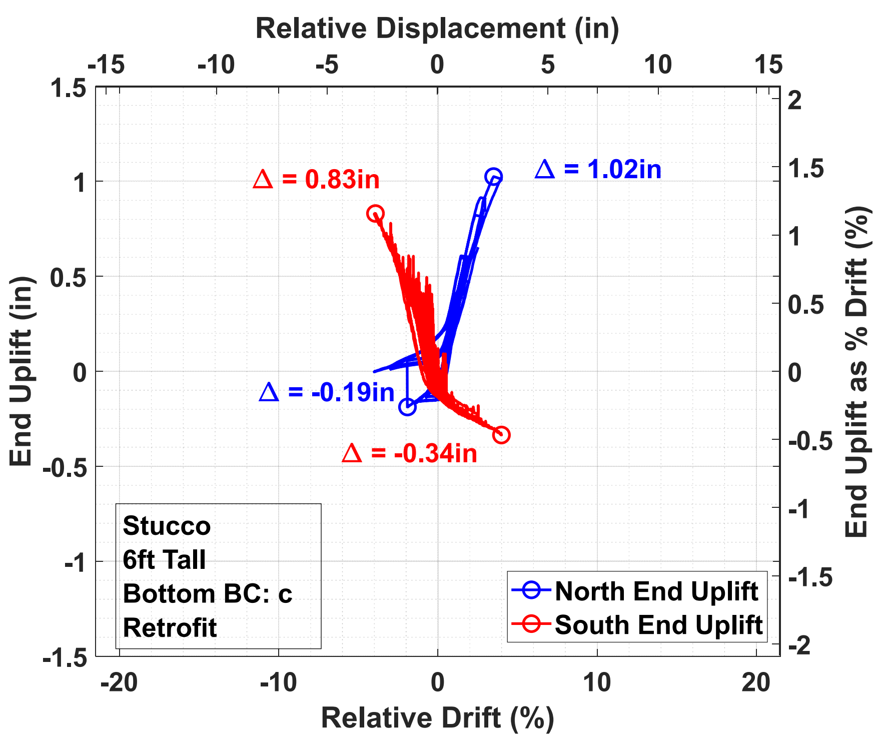


Figure C.45 Specimen A-26 end uplift versus *relative* drift.

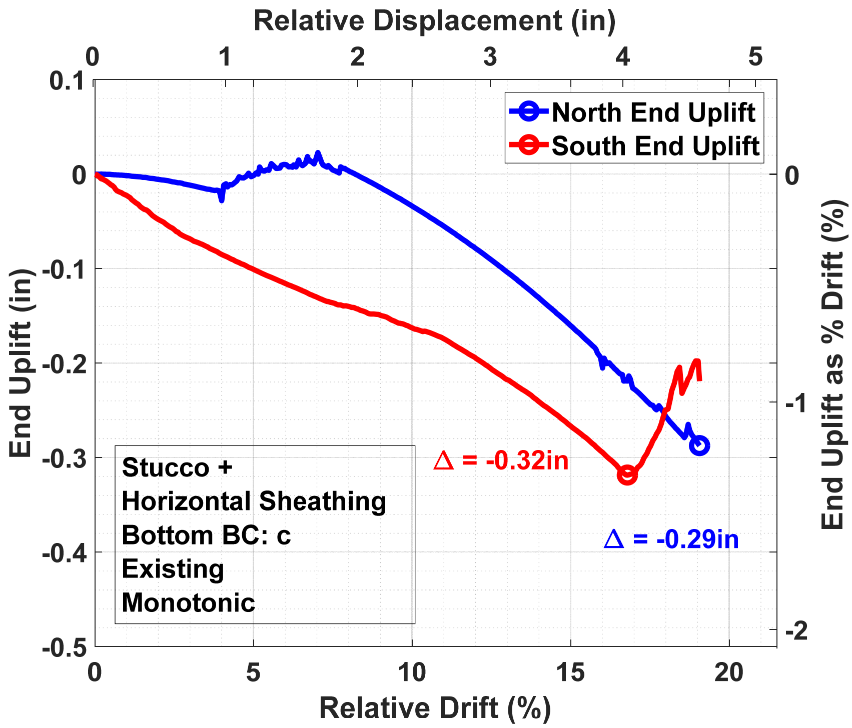


Figure C.46 Specimen A-27 end uplift versus *relative* drift.

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