CYCLIC BEHAVIOR AND REPAIR OF STUCCO AND GYPSUM SHEATHED WOODFRAME WALLS: PHASE II

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CUREE provides a means to organize and conduct a large research project that mobilizes the capabilities of numerous universities, consulting engineering firms, and other sources of expertise. Examples of such projects include:

- Organization of the large, multidisciplinary conferences on the Northridge Earthquake for the National Earthquake Hazard Reduction Program federal agencies to bring together researchers and users of research;
- Participation in the SAC Joint Venture (CUREE being the “C”), which conducted a $12 million project for the Federal Emergency Management Agency to resolve the vulnerabilities of welded steel frame earthquake-resistant buildings that surfaced in the 1994 Northridge Earthquake;
- Management of the CUREE-Caltech Woodframe Project, a $7 million project funded by a grant administered by the California Office of Emergency Services, which included testing and analysis at over a dozen universities, compilation of earthquake damage statistics, development of building code recommendations, economic analyses of costs and benefits, and education and outreach to professionals and the general public;
- Establishment for the National Science Foundation of the consortium that will manage the Network for Earthquake Engineering Simulation;
- Conducting research investigations in the USA jointly with Kajima Corporation researchers in Japan since the 1980s;
- Conducting the Assessment and Repair of Earthquake Damage Project, aimed at defining objective standards for application to buildings inspected in the post-earthquake context;
- Participation as a sub-awardee to the Southern California Earthquake Center in the Electronic Encyclopedia of Earthquakes project funded by the National Science Foundation.
The goal of the Assessment and Repair of Earthquake Damage Project is to develop guidelines that provide a sound technical basis for use by engineers, contractors, owners, the insurance industry, building officials, and others in the post-earthquake context. Based on experimental and analytical research and a broad discussion of the issues involved, the guidelines produced by the project will reduce disparities in the evaluation of building damage and the associated need for repairs.
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Abstract

In an effort to gain a better understanding of the seismic behavior of woodframe structures, the Consortium of Universities for Research in Earthquake Engineering (CUREE), with funding from the California Earthquake Authority (CEA) initiated a woodframe wall testing project at the University of California, San Diego. The project was conducted in two phases. Phase I (Arnold et al, SSRP 2002/07) investigated the response of woodframe walls having boundary conditions consistent with the first level walls of a two-story structure, and Phase II (presented herein) investigated the response of woodframe walls having boundary conditions consistent with a single-story structure.

Common construction techniques of the 1970s were targeted as the prototype test specimen since it is believed that this style of construction most consistently reflects the current majority of existing woodframe structures. A typical 7/8 in. three-coat portland cement plaster system was used for the exterior wall finish and 1/2 in. gypsum wallboard was used as the interior wall finish. No structural sheathing was applied to the framing to increase the lateral resistance. Two separate wall configurations with openings were tested under reversed pseudo-static cyclic loading conditions. The damage thresholds previously defined in Phase I were used in Phase II as the drift ratios associated with changes in structural performance and qualitative damage states. Drift levels of 0.2%, 0.4%, and 0.7% were determined as the drift ratios demarking the relevant performance regimes and damage states and were used as milestones in all subsequent tests for purposes of repair and performance assessment.

Walls with single-story boundary conditions exhibited ultimate strengths of 1,250 pounds per net foot of wall, which is roughly 2/3 of the ultimate strength of walls with two-story boundary conditions tested in Phase I. Walls with stucco continuous over the foundation stemwall exhibited higher initial stiffness and slightly greater ultimate strength relative to walls terminated at the sill plate. This effect was more pronounced for the two-window wall configuration with a continuous sill plate. The introduction of 1/2 in. chop strand fibers in the stucco basecoats was found to have no significant effect on the overall performance of the walls. Wall repair techniques effectively restored the original strength of the walls. When the repaired walls were reloaded to the damaging drift level, local variations of damage occurred and were dependent on the repair method,
but the global crack patterns were similar to those observed during the initial loading cycles.
Acknowledgements

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Chapter 1  Introduction

1.1  Background

On January 17, 1994, the Northridge Earthquake of moment magnitude 6.7 hit Southern California. In terms of economic loss, this earthquake ranks as the largest single natural disaster in United States history. The insured residential damage totaled $12.5 billion, almost all of which occurred in structures of woodframe construction (EERI, 1995). In the months following the earthquake, engineers and trade professionals alike agreed that much research had to be conducted in an effort to relate visible damage to structural capacity of various woodframe wall systems.

Because of the relative lack of information and testing on the seismic response of woodframe structures, the performance levels of various woodframe systems is widely disputed. Much confusion also exists on how to properly design such systems considering the wide range of allowable design values used in practice over the years for the individual wall constituents (i.e. gypsum wallboard, cement-based plasters, etc). Because of this confusion, insurance company claim adjusters and engineers in the field commonly conflict on the assessment of damage sustained to a wall or home when making an insurance claim appraisal. Many buildings became total losses even though they had relatively minor damage. In some cases, significant but subtle damage was not initially identified.

By the early 1970s, residential woodframe structures were generally built with a defined lateral force resisting system utilizing the finish materials (ICBO, 1970). The widely varied installation techniques of the finish materials created varying performance levels and became more of a concern as the construction rate began to increase. A large portion of the existing woodframe construction in California can be attributed to the construction boom of the late 1960s to early 1980s. Because the rate at which new homes were being built was so high, more efficient building materials and finishes were sought out and used. The most common finish materials used in construction of woodframe residential construction became portland cement plaster for exterior finish and gypsum wallboard (drywall) for interior finish.
1.2 Portland Cement Plaster Construction

Portland cement plaster, commonly referred to simply as stucco, is a cementitious material similar to mortar in composition. Advantages of stucco include versatility of design and aesthetic appeal, variety of finish styles and color, water resistance, good performance in a variety of climates, good fire-resistant properties, low maintenance and life-cycle cost ratio, and impact resistance. A wall system utilizing stucco is mainly comprised of four constituents: portland cement plaster, reinforcing mesh, membrane, and structural framing, typically wood or steel studs (see Figure 1.1).

Portland cement plaster is commonly applied in one to three coats. The three-coat system used in this study involves first, a 3/8-in. scratch coat, second, a 3/8-in. brown coat, and finally, a 1/8-in. finishing coat. In addition to providing tensile reinforcing of the stucco, the reinforcing mesh provides a means of securing the stucco and the wall-framing members via a variety of fastener options such as furring nails or staples. Varying sizes of wire openings and gages are available for the reinforcing mesh. The building paper membrane serves as a water barrier between the exterior stucco and the interior framing. Initially, the membrane material was commonly a heavy-duty material such as #30 felt, but due to the poor vapor permeability of felt, a Grade D type building paper has replaced the use of felt for the weather barrier. When properly applied, the membrane creates a weather resistive barrier preventing decay and other possible damage to the wood framing caused by water that penetrated the stucco. Self-furred, paper-backed lath is an alternative to the wire and paper membrane, however the purpose is the same. Another common feature of stucco walls is the implementation of weep screeds at the bottom perimeter, which allow for the exit of any moisture that penetrates the plaster and is intercepted by the building paper.

Because water is the catalyst for the cement curing process, shortening or shrinkage of the plaster will inevitably occur as the mixing water evaporates and the cement cures. This shrinkage will typically create randomly distributed hairline cracks in

---

1 The one-coat system, primarily used in hotter climates, was developed in the early eighties and continues today. This system includes a weather barrier of light building paper, followed by expanded polystyrene, with a wire membrane over the foam and usually a fiber-reinforced proprietary premixed stucco. The one coat system can also have a color coat added if desired.
solid stucco panels. Where openings are present, the cracks will tend to emanate from the corners of openings in the stucco panels. Another common cause of non-structural cracking is due to the difference in the coefficients of thermal and moisture expansion between the plaster and the wood framing. Many new innovations have been proposed in order to reduce these cracks which include: the implementation of high-strength stucco, the use of fiberglass tape as a skin beneath the finish coat, small 1/2 in. fiberglass or polypropylene fibers introduced as an additive to the scratch coat, and acrylic additives introduced into the finish coat. Even though the cracks are non-structural, homeowners and insurance companies are very concerned with this level of cracking (Northwest, 1997).

1.3 Gypsum Wallboard Construction

Gypsum wallboard construction, commonly referred to as drywall, became popular in the 1950s, but it was not until around 1970 that nearly 90% of all new residential construction was built using gypsum wallboard as an interior finish material for both ceilings and walls. Drywall replaced the previously used gypsum lath and plaster. The latter method used a variety of lath materials and configurations to attach the plaster to the framing members. One of the main advantages of the lath and plaster method is the superior fire resistance. These systems are the best interior wall and ceiling finishes when considering long-term performance, durability and a truly monolithic surface, but gypsum wallboard is much quicker to install and more cost effective.

Often incorrectly referred to by the proprietary name “Sheetrock,” gypsum wallboard is a wall finish material that consists of a gypsum slurry solidified into panels of desired length and width, most commonly 4 ft by 8 ft. The basic gypsum wallboard system is comprised of the gypsum wallboard panels attached to the structural framing members using mechanical fasteners; often phosphate covered cooler nails or screws. At locations where individual wallboard panels meet, either paper or fiberglass joint tape and joint-type setting compound is used to finish the joint, rendering it unseen. The increased use of gypsum wallboard can be attributed to the inherent advantages such as sound control, speed and relative cleanliness of construction, availability of attractive and unique final finishes, and overall economy (Bureau, 1972).
1.4 CEA/CUREE Wall Testing Project

As part of a research project funded by the Consortium of Universities for Research in Earthquake Engineering (CUREE) under contract to the California Earthquake Authority, a testing program to assess earthquake damage in residential buildings was initiated at the University of California, San Diego. The objectives of the research are as follows:

1. determination and documentation of correlation between story drift and qualitative damage states based on the visible condition of wall finishes,
2. documentation of typical patterns of seismic damage to walls with openings and stemwall effects (Phase II),
3. determination of the aesthetic and structural performance of various finish repair methodologies, and
4. influence of boundary conditions on the structural response of the walls.

The project was conducted in two separate phases. Phase I (Arnold et al, SSRP 2002/07) involved testing having boundary conditions consistent with the first level walls of a two-story structure. Also included in the Phase I report is a review of literature pertinent to the testing of woodframe structures with openings and varying finish materials. Phase II involved the testing of identically built walls as in Phase I, but having boundary conditions consistent with the walls of a single-story structure. In order to provide results consistent with the majority of existing construction, the scope of both Phases I and II focused on construction techniques commonly used in the 1970s.

1.4.1 Definition of Damage States

One of the objectives of the study is to determine levels of drift associated with various levels of damage. In the project proposal, three damage states were qualitatively defined as follows.

Stage 1 damage is described as the wall having displaced through a near linear-elastic response, with minimal strength and stiffness degradation. New cracks may develop while the attachment of finish to framing remains sound with virtually no structural damage. Cracking of the joint compound around the edges of the fasteners, commonly referred to as fastener “popping,” may be associated with this damage state. All finish damage should be readily repairable.

Stage 2 damage is associated with a slight reduction in wall stiffness. Stucco
cracks associated with Stage 1 damage state increase in length and width and new cracks branch from existing cracks. Wallboard damage is more readily apparent with the initiation of cracking along the corner bead at the window openings. Fastener popping and wallboard joint cracks and tearing are associated with this damage state. The damage should be readily repairable without requiring the removal of any portions of the finish.

Stage 3 damage is defined as the damage state associated with some softening or loss of stiffness. Significant finish damage is expected to occur and large crack widths and lengths will be evident on both the interior and exterior finish. Partial finish removal and replacement may be necessary; nevertheless, the damage should be readily repairable.

The level of drift associated with failure will have significant strength degradation past the ultimate strength of the wall. Large crack widths of stucco and gypsum wallboard, spalling of stucco at corners of openings, relative rotation of gypsum panels and the cooler nails pulling through the wallboard are all associated with the failure damage state. Other forms of non-repairable damage may be apparent as well.

It should be noted that the previously defined damage states are subjective. The purpose of the definitions was as a guide for quantifying wall finish damage. Descriptions such as “minimal” and “slight” do not have values assigned to them, but are to be used along with engineering judgment to assign a level of drift to the definitions, which are unique to this report.

The test setup, specimen construction and specifications, loading history, and instrumentation are all covered in Chapter 2. Non-seismic finish cracking and the possible causes are covered in Chapter 3, as well as any observed non-seismic cracks in the finishes or issues for Walls 5 to 12. In Chapter 4, the test results of the first two pair of test specimens are presented. The observed and measured response of the test specimens was carefully documented for all levels of drift associated with the prescribed loading history. Using all useful data gathered during the testing of the first pair of specimens, various levels of drift were associated with the prescribed qualitative damage state definitions. Walls 9 and 10 were destroyed by a hydraulic malfunction in the laboratory that occurred during the signal check, just before testing. All documented damage and any valid data recovered from the accident are presented in Chapter 5.

Chapter 6 covers the testing of Walls 11 and 12. This pair of test specimens had a
concrete stemwall introduced so that information regarding stucco cracking at the sill plate and the effects on wall response could be investigated. Chapter 6 also covers damage repair of the wall finishes. In Chapter 7, the relative effects of key test variables are evaluated. Chapter 8 presents the conclusions drawn from the project and recommendation for future studies of various woodframe construction issues.
Figure 1.1 Open Stud Construction
Chapter 2 Testing Program

2.1 Introduction

Eight test specimens were constructed and tested for Phase II of the CEA/CUREE Woodframe Wall Testing Project. Specimen designation for Phase II follows the Phase I numbering scheme and the wall specimens are referred to as Walls 5 to 12 since Phase I involved Walls 1 to 4. The testing matrix for Phase I of the project is shown in Table 2.1.

All Phase II wall specimens were cyclically loaded to failure using the CUREE loading protocol for the testing of woodframe structures (Krawinkler, 2001) and carried out under reversed pseudo-static cyclic loading. For testing purposes, failure is defined as the point at which the applied load drops for the first time below 80% of the maximum load developed. The original testing plan for Phase II is shown in Table 2.2, but due to an unfortunate malfunction of the hydraulics, two of the wall specimens (Walls 9 and 10) were destroyed before the testing was carried out. The accident is discussed in Chapter 5 of this report. The revised testing plan for Phase II is shown in Table 2.3.

Walls 11 and 12 were loaded up through 0.4% drift and repaired. Once repaired, the walls were reloaded to 0.4% drift, starting from the beginning of the loading protocol to allow evaluation of the performance of the repaired wall during a repetition of the damaging loading. The loading protocol was then continued through failure. This method of loading is described as “two-stage” testing and is shown in Table 2.4.

2.2 Test Setup

A self-reacting steel frame capable of testing two specimens in parallel was used as the test setup. The frame was designed such that out-of-plane motion at the sill plate and double top plate was prevented. A 165-kip, ±6 in. stroke hydraulic actuator was used to load the specimens in displacement control. The actuator was placed approximately at one-third height of the loading column. This allowed for an actuator displacement amplification of three at the top of the wall.

Phase I of the project investigated the behavior of the wall specimens under two-

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It is important to note that most drift levels presented in this report refer to displacement of the odd numbered walls, displacement of which was used to control test displacement. Drift in the other wall of the test pair was typically somewhat greater.
story boundary conditions, and Phase II investigated the behavior of the wall specimens under single-story boundary conditions. The single-story boundary conditions involved the addition of a more flexible member on top of the walls to simulate the approximate stiffness contribution of the ceiling and roof system having ceiling joists perpendicular to the wall specimens. Therefore, instead of having a continuous wide flange section on top of the wall, a 3/8 in. steel strap was lag-bolted along the length of each wall. The approximate single-story dead load of 250 lbs/ft was applied at four locations as equivalent point loads using 1 ft sections of wide flange beam and concrete blocks placed perpendicular to the dead load tubes. The single-story boundary condition testing frame and the various components are shown in Figure 2.1 and the test frame dimensions are shown in Figure 2.2 with one of the test specimens installed into the testing frame.

The testing frame was also modified to fit a 6 in. concrete stemwall to act as the foundation of an existing structure for the testing of Walls 11 and 12 only. This allowed for the continuous application of the stucco over the foundation (i.e. no weep screed), as was common practice in pre-1970s construction. The modified frame with the stemwall is shown in Figure 2.3.

The loading column transferred load through a 50-kip load cell (Figure 2.4) attached to a 3/8 in. steel plate that was lag bolted through a 2 in. by 8 in. D.F. No. 2 loading plate into the double top plate of the wall. MC 6X16.3 sections on either side of the webs of the 1 ft sections of wide flange beams guided the walls to prevent out-of-plane movement. 5-6 in. by 4 in. sections of Teflon covered with grease were placed on either side of the web to reduce any possible friction occurring as the walls displace relative to the guide channels.

To simulate the approximate dead load that the exterior walls of a single-story home would see, approximately 250 lbs/ft of force was imposed upon the wall specimens by way of four structural tubes and the use of actual dead weight. The 250 lbs/ft was approximated as four point loads applied at the locations where the dead load tubes are located as shown in Figure 2.1. The location of the dead load tubes was selected so that actual dead load could be placed on top of the testing frame in two separate segments. This was done so that the uplift for one half of the wall was not resisted by the other half of the wall. The dead weight scheme is shown in Figure 2.5.

The 1 ft sections of wall glider allowed for rotation of the double top plate and
rocking of the individual wall piers for the single-story boundary condition once the uplift force overcame the dead load. The wallslider connection and single-story boundary condition for the top of all wall specimens for Phase II is shown in Figure 2.6. Figure 2.7 shows the testing frame with the walls installed from the ground level where the actuator is visible.

2.3 Wall Construction Details and Material Properties

To simulate the performance of walls in an actual structure, various boundary conditions were implemented during the specimen construction. A 2 in. by 8 in. piece of lumber was added on the top of the double top plate so that a ceiling return was simulated for the gypsum wallboard. Typical corner stud construction was used at specimen ends to simulate the intersecting walls in an actual home. The boundary condition construction details are shown in Figure 2.8 and the boundary conditions are shown in Figure 2.9, which also shows the protruding sill plate where the sill plate was restrained (for all walls except Walls 11 and 12). For Walls 11 and 12, a 6 in. concrete stemwall was constructed so that the horizontal cracking at the sill plate level could be investigated. In older construction (pre-1970s), the stucco typically extended past the sill plate and over the foundation. The stemwall boundary condition is shown in Figure 2.10.

Two different wall configurations were built. One wall configuration had two 4 ft by 3 ft rough window openings, and the other configuration had one 4 ft by 3 ft rough window opening and one 2 ft by 8 in. wide by 6 ft by 10 in. door opening. No holdowns were installed at wall pier boundaries to provide uplift resistance and no structural sheathing was installed to the framing. All headers over wall openings were 4 in. by 6 in. and all anchor bolts were 1/2 in. diameter spaced at 72 in. on center to be consistent with the typical construction practice of the 1970s. All structural framing was gun nailed according to Table 23-II-B-1 of the 1997 Uniform Building Code (ICBO, 1997), which reflected the practice of years past with the exception of the use of a nail gun; nail guns were not commonly used in woodframe construction until the mid-1980s. The structural construction:

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3 While aesthetically pleasing, this construction practice created problems as trapped moisture behind the wall resulted in cracking of the stucco along the sill plate and decay in the sill plate. Code changes in the early 1970s required the installation of weep screeds at the sill plate.
framing elevations for all test specimens are shown in Figure 2.11.

All the lumber used for the structural framing of the test specimens was Douglas Fir No. 2 structural lumber and the sill plates were pressure treated Douglas Fir No. 2. In accord with ASTM D 4442-92 (ASTM, 1995), the moisture content of the framing was taken from a few random stud samples after testing and can be seen in Table 2.5. The moisture content of all framing was under the 1997 Uniform Building Code maximum of 19%.

All framing was constructed using 16d common and 8d common nails where specified. Furring nails with a 3/8 in. cardboard wad were used for the stucco application spaced at 6 in. on center. All pertinent nail information is shown in Table 2.6.

The interior finish of all test specimens was 1/2 in. gypsum wallboard fastened to the framing with 6d phosphate covered cooler nails spaced at 7 in. on center. All gypsum wallboard was 1/2 in. 4 ft by 8 ft panels. The longer length was installed horizontally and all wallboard joints were staggered since this was commonly done in the 1970s (see Figure 2.12). Walls 6 and 8 were constructed having non-staggered wallboard joints to investigate any noticeable difference in strength.

The exterior finish was a three-coat 7/8 in. portland cement plaster. The portland cement plaster application involved first the application of a 3/8 in. scratch coat followed by a 3/8 in. brown coat and finally a 1/8 in. color or finish coat. For Phase II testing purposes, the finish coat used was a smooth coat so that cracks could be more easily mapped and measured than with a textured finish coat that was used in Phase I testing. The smooth coat is commonly referred to as a “Santa Barbara” finish. Line wire, grade D building paper, 17-gage hexagonal wire lath, and furring nails spaced at 6 in. on center were also used to install the stucco. Phase I had 1/2 in. chop strand fibers introduced into the scratch and brown coats for all walls tested. Phase II had the fibers introduced for Walls 5 and 6 only to assess their effect on the wall strength.

The stucco boundaries were confined by a 7/8 in. Grade 10 stucco stop commonly referred to as “J” molding because of its shape. A bare wood framed wall specimen is shown in Figure 2.13. The common three-coat stucco procedure involves first the building paper and wire lath application (Figure 2.14) followed by the scratch coat (Figure 2.15), the brown coat (Figure 2.16) and finally the color or finish coat (Figure 2.17). The following components were used in the stucco application:
2-ply Jumbo Tex building paper, grade D
Self-furring woven wire lath (k-lath) 17 gauge with 1-1/2 in. hexagonal openings, galvanized
Gauge 16 tie wire (diameter = 0.0625 in.)
Riverside plastic cement (scratch coat, brown coat)
Expo base #4 stucco (finish coat)
1/2 in. chop strand fibers mixed with stucco basecoats (Walls 5 and 6)

From each coat of stucco, three 2 in. diameter, 6 in. tall cylinder samples were collected and tested for compressive strength on the day of wall testing. The results are shown in Table 2.9. The scratch coat and the brown coat differ only by the addition of approximately 2 to 3 more shovels of sand per bag of plastic cement for the brown coat compared to the scratch coat. A plaster sand analysis was conducted on the sand used in the stucco application process to see if it properly met the requirements of ASTM C-144. The results are shown in Figure 2.18.

2.4 Loading History

The CUREE Abbreviated Loading History for Ordinary Ground Motions (Krawinkler et al, 2001), specifically developed for the testing of woodframe specimens, was used for this study. The loading protocol is based on initially determined reference displacement, which can be determined from a monotonic test of the specimen. The reference displacement is the deformation at ultimate strength. Because of the limited number of available test specimens, the monotonic test was not performed. Rather, literature on stucco and gypsum wallboard testing and engineering judgment were used to establish the reference displacement ($\Delta$). A $\Delta$ of 1 in. was selected for all walls in this study. A graphical definition of $\Delta$ can be seen in Figure 2.19. The test results for Phase I showed that the selected reference displacement was accurate. All tests were carried out under displacement control based on the deformation of Walls 5, 7, 9, and 11 (the control walls). Walls 6, 8, 10, and 12 acted as slave test specimens, which is evident when examining the wall hysteresis curves. The even numbered walls displaced further than the control walls due to the geometric differences causing a difference in wall stiffness. Thus, the walls with the door opening (the even numbered walls) effectively sustained a more aggressive displacement loading protocol.
Figure 2.20 shows the loading protocol used for all testing. Initiation cycles begin the test and are intended to be used as an instrumentation check, and can also be used to check the response at small amplitude displacements representing small seismic events. The remainder of the cycles are symmetric primary cycles followed by a specified number of symmetric trailing cycles.

The most obvious feature of the loading history is that after the primary cycle of displacement, the trailing cycles (a larger number for low amplitude displacements and fewer for larger amplitude displacements) are scaled to 75% of the amplitude of the primary cycles. Figure 2.21 shows the loading convention for all figures representing each wall and the exterior and interior elevations. The positive and negative directions of displacement are shown as if facing the finish being discussed. This convention is used to reference the direction of loading for the remainder of the report. Because loading phases were always terminated at zero load at the end of the negative loading direction, all permanent deformation or residual drifts of the wall specimens are in the negative direction.

2.5 Instrumentation

An extensive instrumentation plan was used to capture localized effects in addition to the global response of the test specimens. A combination of displacement transducers, load cells, and inclinometers were placed in specific locations where the desired effect would be best exhibited. Table 2.10 to Table 2.15 show the individual instrumentation descriptions for all tests, and Figure 2.22 to Figure 2.27 shows the graphical instrumentation scheme. All positive measurements are in the direction of the arrows for all instrumentation.

Figure 2.28 shows the load cell attached to each of the anchor bolts used to secure the wall specimen to the testing frame. Figure 2.29 shows an inclinometer used to measure the stucco panel rotation and the strain gage rosettes attached to the stucco. Figure 2.30 is an example of the linear potentiometers used to measure sill slip and sill uplift (±1.5 in.) and Figure 2.31 shows the string potentiometers (±7-1/2 in.) used to measure the global wall displacements and global wall shear deformations. The measured and documented data is presented in the chapters to follow.
### Table 2.1 Phase I Test Matrix

<table>
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<th>Test No.</th>
<th>Specimen Designation</th>
<th>Openings</th>
<th>Testing Method</th>
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<td>1</td>
<td>Two windows</td>
<td>CUREE protocol to failure</td>
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<td></td>
<td>2</td>
<td>One window, one door</td>
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<tr>
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<td>Two windows</td>
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<td>four-stage testing</td>
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### Table 2.2 Phase II Test Matrix

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<td>Two windows</td>
<td>CUREE protocol to failure</td>
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### Table 2.3 Revised Phase II Test Matrix

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Table 2.4  Two-Stage Testing

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<td>2.5%</td>
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Table 2.5  Moisture Content

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<th>Wall Specimen</th>
<th>Original mass (grams)</th>
<th>Oven-dry mass (grams)</th>
<th>MC %</th>
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<td>8</td>
<td>348.8</td>
<td>303.5</td>
<td>14.93</td>
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Table 2.6  Nail Properties

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<th>Nail Type</th>
<th>Diameter</th>
<th>Length</th>
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</thead>
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<td>3 1/2 in.</td>
</tr>
<tr>
<td>8d Common</td>
<td>0.131 in.</td>
<td>2 1/2 in.</td>
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<tr>
<td>5d Cooler</td>
<td>0.086 in.</td>
<td>1 5/8 in.</td>
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<tr>
<td>Furring</td>
<td>0.1055 in. (3/8 in. wad)</td>
<td>1 1/2 in.</td>
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</table>
Table 2.7  Moisture Content

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<tr>
<td>5d Cooler</td>
<td>0.086 in.</td>
<td>1 5/8 in.</td>
</tr>
<tr>
<td>Furring</td>
<td>0.1055 in. (3/8 in. wad)</td>
<td>1 1/2 in.</td>
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Table 2.9  Stucco Compressive Strength

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<th>Coat</th>
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<tr>
<td>Scratch</td>
<td>1660</td>
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</tr>
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<td>Scratch w/ Fiber</td>
<td>1480</td>
<td>&gt;28</td>
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<tr>
<td>Brown</td>
<td>1530</td>
<td>&gt;28</td>
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<td>Brown w/ Fiber</td>
<td>1450</td>
<td>&gt;28</td>
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<td>Finish</td>
<td>370</td>
<td>&gt;28</td>
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Table 2.10  Wall 5 Instrumentation

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<th>Instrument</th>
<th>Name</th>
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<tbody>
<tr>
<td>sill uplift (location 1)</td>
<td>WSU1</td>
<td>potentiometer</td>
<td>sill uplift at northern end of wall</td>
</tr>
<tr>
<td>sill uplift (location 2)</td>
<td>WSU2</td>
<td>potentiometer</td>
<td>sill uplift at southern end of wall</td>
</tr>
<tr>
<td>corner stud uplift (location 1)</td>
<td>WCSU1</td>
<td>potentiometer</td>
<td>corner stud uplift at northern end of wall</td>
</tr>
<tr>
<td>corner stud uplift (location 2)</td>
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<td>potentiometer</td>
<td>corner stud uplift at southern end of wall</td>
</tr>
<tr>
<td>sill slip (location 1)</td>
<td>WSS1</td>
<td>potentiometer</td>
<td>sill slip at northern end of wall</td>
</tr>
<tr>
<td>sill slip (location 2)</td>
<td>WSS2</td>
<td>potentiometer</td>
<td>sill slip at southern end of wall</td>
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<tr>
<td>global wall shear displ. (location 1)</td>
<td>WWSD1</td>
<td>string pot.</td>
<td>deformation between wall panel corners</td>
</tr>
<tr>
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<td>WWSD2</td>
<td>string pot.</td>
<td>deformation between wall panel corners</td>
</tr>
<tr>
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<td>WWD</td>
<td>string pot.</td>
<td>global wall displacement (control displ.)</td>
</tr>
<tr>
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<td>WWF</td>
<td>50 kip load cell</td>
<td>global wall force</td>
</tr>
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<td>WWAF1</td>
<td>load cell</td>
<td>force at shear anchor</td>
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<tr>
<td>anchorage force (location 2)</td>
<td>WWAF2</td>
<td>load cell</td>
<td>force at shear anchor</td>
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<td>force at shear anchor</td>
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<tr>
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<td>WWAF4</td>
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<td>force at shear anchor</td>
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<td>rotation of central wall pier</td>
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<tr>
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<td>WSPR2</td>
<td>inclinometer</td>
<td>rotation of pier above window</td>
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<tr>
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<td>rotation of pier below window</td>
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Table 2.11  Wall 6 Instrumentation

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Figure 2.1  Single-Story Boundary Condition Setup

Figure 2.2  Test Frame Dimensions

Figure 2.3  Single-Story Boundary Condition Setup with Stemwall
Figure 2.4 50-kip Load Cell Attachment

Figure 2.5 Dead Load Configuration

(a) North  (b) South

Figure 2.6 Wall Glider Connection
Figure 2.7 Testing Frame
Figure 2.8 Wall Construction Details
(a) Ceiling Return

(b) Corner Stud

(c) Stucco Return and Sill Restraint

Figure 2.9 Wall Specimen Boundary Conditions
(a) Bare Framing

(b) Lath and Building Paper Applied

(c) Termination of Lath and Building Paper at Sill Plate

(d) With Wallboard Installed

(e) After Brown Coat

(f) After Finish Coat

Figure 2.10  Stemwall Boundary Conditions
Figure 2.11 Construction Framing Elevations
(a) Walls 5, 7, 9, and 11

(b) Walls 6 and 8

(c) Walls 10 and 12

Figure 2.12 Gypsum Wallboard Configuration
Figure 2.13  Bare Wood Framing

Figure 2.14  Wall after Lath and Building Paper Application
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Figure 2.16  Wall after Brown Coat Application
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Figure 2.18 Plaster Sand Analysis
\[ \Delta = 0.6 \times \Delta_m \]

Figure 2.19 Definition of \( \Delta_m \) and \( \Delta \) According to the CUREE Protocol

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Figure 2.30  Sill Uplift and Sill Slip Potentiometers

Figure 2.31  Global Wall Force and Shear Displacement String Potentiometer
Chapter 3  Non-Seismic Cracking

3.1  Introduction

Cracking of portland cement plaster is most commonly caused by shrinkage of the stucco as part of the normal curing process, thermal contraction, or some form of structural movement creating excessive stresses at locations of stress concentrations or weaknesses in the finish materials. Although it is nearly impossible to eliminate all stucco cracking in a structure, various methods and procedures are available to minimize the level of stucco shrinkage cracking.

3.2  Stucco Shrinkage

The most common application of portland cement plaster is the three-coat system, which involves the application of a 3/8 in. scratch coat, a 3/8 in. brown coat, and a 1/8 in. finish coat. One major benefit of a three-coat system is that sufficient shrinkage of each preceding layer takes place so that each new layer bridges over any cracking in the substrate layer. The finish coat functions as a decorative color coat to complete the process. Certain fine grained or smooth textures accentuate cracks in stucco while heavier textures tend to hide the stucco cracks. Even when proper curing techniques and recommended curing times between coats are followed on a project, the stucco still may develop visible cracks.

3.3  Geologic Hazards

Geologic conditions in the vicinity of a structure can also cause cracking in the stucco. Certain crack patterns are diagnostic indicators, which implicate specific structural movements relative to a particular geologic hazard (Audell, 1996). The most common geologic hazards influencing structural behavior are soil subsidence, soil expansion, landslides/slope creep, and ground shaking from seismic activity. The swelling, shrinking, and lateral spreading of soil can all cause significant cracking in the wall finish materials. Foundation settlements creating differences in the finish floor elevations are common causes of stucco cracking, and may be the result of incorrectly compacted fill or insufficient footing depth or foundation type (continuous strip-footing versus a pier and grade beam foundation).
3.4 Wood Shrinkage

Another common cause of stucco cracking is the stress caused by the shrinkage of the framing lumber caused by the drying out of the wood after installation. The moisture content of most commercially available lumber typically ranges from 15%-20% by weight for “green” lumber. Kiln-dried lumber, which has a lower moisture content upon sale is also available but is seldom used on the west coast.

All lumber has a fiber saturation point above which the lumber dimensions no longer change with the increase of water content. Most lumber has a fiber saturation point of 28%-30%, depending on the species. Wood is dimensionally stable when the moisture content is above the fiber saturation point. Wood changes dimension as it gains or loses moisture below that point. Wood shrinks when losing moisture and swells when gaining moisture. The year-round average equilibrium moisture content of studs, joists, and rafters in heated buildings is about 10% and may fluctuate with the change in seasons. Moisture changes in the wood may result in warping, checking, splitting, or other performance problems.

Wood is an anisotropic material with respect to the shrinkage characteristics. It shrinks most in the direction of annual growth rings (tangentially), about one-half as much across the rings (radially), and only slightly along the grain (longitudinally). Tangential shrinkage is on the average of 8% and radial shrinkage is near 4% for most species. The combined effects of radial and tangential shrinkage can distort the shape of wood because of the difference in shrinkage and the curvature of the annual rings.

Longitudinal shrinkage of wood is quite small. The longitudinal shrinkage from green to oven-dry condition is only 0.1% to 0.2% for most species of wood, and for all practical purposes can usually be ignored. The longitudinal direction is in the direction of the height of a building with respect to the studs. Thus, the majority of the shrinkage due to the lumber is from the thickness of the wall plates and the depth of the rim joists and all intersecting floor and ceiling joists. With proper construction detailing, any cracking caused by the shrinkage or swelling of lumber can be greatly reduced (Breyer et al, 1999).

3.5 Observed Non-Seismic Cracking for Walls 5 to 12

Walls 5 and 6 had 1/2 in. chop strand fibers introduced into the stucco basecoats
to evaluate the effects of the fibers on stucco shrinkage cracking. The scratch and brown coats had virtually no observable shrinkage cracks. A smooth coat or “Santa Barbara” finish was applied to the walls and checked the following day for cracking. The finish coat cracking is shown in Figure 3.1 and Figure 3.2. The additional cracks and the lengthening or widening of any of the existing cracks after the finish coat application that occurred while moving the test specimens into the testing frame is shown in Figure 3.3. These cracks were present before any testing was performed.

Walls 7 through 12 had no fibers introduced into the basecoats and all stucco shrinkage cracking that occurred was documented. No shrinkage cracking was observed in the scratch coat for any of the wall specimens. The moist air during the time of application had a significant effect on the lack of shrinkage cracking. The average relative humidity in San Diego, California over the past 30 years ranges from 75% in the morning to 60% in the afternoon (National Weather Service). These numbers will be slightly higher for La Jolla, California.

The brown coat also performed very well with respect to amount of shrinkage cracking from the stucco curing process. After one week, no cracks were observed for all wall panels, but after two weeks some cracks were observed at various locations in the stucco brown coat at wall opening corners and is shown in Figure 3.4.

Figure 3.5 shows the stucco cracking that formed in the finish coat and it can be seen that at most locations where a crack formed in the brown coat, an identical crack formed in the finish coat at the same location as early as 24 hours later, although the crack widths were smaller. Figure 3.6 to Figure 3.8 show the observed cracking in the brown and finish coats at these locations and Figure 3.9 shows the observed cracking in the brown coat of Wall 10. Walls 9 and 10 had no visible shrinkage related cracks in the finish coat. Figure 3.10 shows the cracking in the stucco that was documented before testing. These cracks occurred while transferring the walls from outside and into the testing frame.

Figure 3.11 shows the observed shrinkage cracking that occurred in Wall 11. No shrinkage cracks were observed in Wall 12. Figure 3.12 shows the observed stucco finish cracking before the walls were tested. The documented shrinkage crack in the brown coat of Wall 11 did not reflect in the finish coat, and the finish coat had no significant cracks other than small stress cracks and some “checking” or “burning” of the finish coat.
shown in Figure 3.13. Small hairline cracks are very common with a smooth finish coat and are to be expected.
Figure 3.1  Stucco Cracks in Finish Coat (Fiber)
Figure 3.2  Stucco Cracks in Finish Coat
Figure 3.3 Stucco Cracks Before Testing

(a) Wall 5

(b) Wall 6
Figure 3.4  Stucco Cracks in Brown Coat
Figure 3.5 Stucco Cracks in Finish Coat
Figure 3.6  Wall 7 Stucco Cracks

(a) Brown coat

(b) Finish coat
Figure 3.7 Wall 7 Stucco Cracks

(a) Brown coat

(b) Finish coat
Figure 3.8 Wall 8 Stucco Cracks

(a) Brown coat

(b) Finish coat
Figure 3.9  Stucco Cracks in Brown Coat
Figure 3.10  Stucco Cracks Before Testing
Figure 3.11  Wall 11 Stucco Shrinkage Cracking in Brown Coat
Figure 3.12  Finish Coat Stucco Cracking Before Testing
Figure 3.13  Stucco Finish Coat Cracking
4.1 Introduction

The performance criteria and damage state regimes developed in Phase I were used to evaluate the test specimens of Phase II. All test specimens in Phase II were loaded and partially restrained along their top edge to simulate the walls of a one-story structure (see Chapter 2 for specimen details).

All Phase I wall specimens had 1/2 in. chop strand fibers in the stucco scratch and brown coats. For Phase II of the project, only Walls 5 and 6 had chop strand fibers in the stucco basecoats to determine the influence, if any, on the strength of the test specimens. The purpose of the chop strand fibers is to reduce shrinkage cracking that may occur during the stucco curing process. These fibers were not commonly used in the stucco application process until the mid-1980s.

All walls tested in Phase II were monitored for relative magnitude of visual damage and finish crack widths at each displacement level so that correlations between Phase I and Phase II could be made. The measured response of the walls was also compared with Phase I for all drift levels.

4.1.1 Portland Cement Plaster Residual Crack Width As an Index

The cracks in the stucco were used to provide a baseline for comparison at different drift levels because the wallboard cracks were often difficult to measure and the damage to the wallboard was not as obvious at small displacements. Because of the large difference in the initial stiffness between the stucco and the gypsum wallboard, the stucco attracted the majority of the applied load at the small displacement cycles. As a result, the damage to the exterior finish was more readily apparent.

Maximum and residual stucco crack widths were measured at all drift levels associated with the prescribed loading protocol. The maximum stucco crack widths refer to widths measured while the test specimens were held at the peak displacement for each displacement level. The residual crack widths refer to widths measured once the walls were unloaded to zero force after each displacement level. The residual crack widths were used for comparison purposes because, after a seismic event, only the residual crack widths are measurable. Only the single largest crack width that occurred at each opening corner was measured. The measurement of all crack widths in the stucco would dilute
the average width measured for each displacement level, since the cracks that formed at the openings corners were consistently the largest. The average was computed by taking the sum of the widths divided by the number of locations where a measurement was made.

4.2 Damage State Response Regimes

A large volume of data were collected over the course of the test, including crack width measurements, visual examination of the condition of finishes and photo documentation at specific milestones in the test, as well as a continuous record of various transducer data. For ease of presentation, the response history of the walls has been divided into five regimes of behavior, identified by the end point of each regime for the control wall (determined in Phase I) as follows:

- 0.2% drift limit – 0.0% to 0.2% drift
- 0.4% drift limit – 0.2% to 0.4% drift
- 0.7% drift limit – 0.4% to 0.7% drift
- ultimate strength – 0.7% to ultimate strength
- failure – ultimate strength to failure

It is important to note that the drift range in each regime is exact for Walls 5, 7, and 11, which were controlled and approximate for Walls 6, 8, and 12, which were not controlled and acted as slave test specimens. In general, due to their greater flexibility, the drift of Walls 6, 8, and 12 is greater than the drift of Walls 5, 7, and 11 throughout the loading history. Wall behavior in each regime is presented in the following sections. Unless noted otherwise, behavior of the two walls was similar.

4.3 0.2% Drift

Wall behavior up to 0.2% drift is characterized by a very stiff, nearly linear elastic response with minor cracking of finishes and no deterioration of behavior during trailing cycles. The wall responses for this stage can be seen in Figure 4.1 and Figure 4.2. Because the testing was conducted under displacement control using Walls 5 and 7, the maximum imposed displacement for Walls 5 and 7 always reflected the target level of drift. Since the wall specimens were not of equal geometry, Walls 6 and 8 always had a larger maximum imposed displacement. For the 0.2% drift cycles, Walls 5 and 7 had a maximum displacement of 0.20 in. and Walls 6 and 8 had a maximum imposed
displacements of 0.341 in. and 0.337 in. respectively (identified as [0.34%] in subsequent references and figure captions). The corresponding residual drifts at zero wall force for Walls 5 to 8 were 0.07 in., 0.219 in., 0.043 in., and 0.0167 in. respectively.

The net lateral resistance of each wall specimen is calculated by dividing the maximum applied load at the corresponding drift by the net wall length (total wall length minus wall opening widths). The maximum net lateral resistance at 0.2% [0.34%] drift for Walls 5 to 8 is 879 lbs/ft, 656 lbs/ft, 777 lbs/ft, and 515 lbs/ft respectively, considering both positive and negative displacement cycles. The average force resisted for Walls 5 to 8 at 0.2% [0.34%] drift was near 50% of the average ultimate load of all walls for both the positive and negative displacement cycles.

4.3.1 Portland Cement Plaster Damage

Stucco finish cracking produced by cyclic loading up to 0.2% [0.34%] for Walls 5 to 8 is shown in Figure 4.3 and Figure 4.4. All stucco crack lengths were documented while the wall was held at the prescribed drift. The crack length was marked on the wall with a tick mark and a number that represented the cycle number when the crack occurred. The crack widths shown in parentheses are the maximum crack widths measured while the walls were held at the prescribed displacement. The residual crack widths are not in parentheses and were measured at zero wall force. Hairline cracks defined in this report are cracks that were visible but had a width of less than 0.002 in. and are designated by an “HC.”

Stucco cracks initiated at the wall opening corners and propagated at near 45-60 degrees from the horizontal, depending on the opening location along the wall. Any stucco cracks that existed at wall opening corners before the testing began all increased in length and width. Some of the existing stucco cracks did not increase in length or width because they were not in a location of high stress under lateral loading, typically within the stucco piers away from the opening corners. Figure 4.5 to Figure 4.10 shows the typical stucco cracks that formed at window opening corners for Walls 5 to 8. At each wall opening corner, a scale was placed for visual purposes. Each increment represents 1/4 in. (the inset shows the location on the wall where the photo was taken). Figure 4.7 shows where the stucco cracks that formed at adjacent window opening corners joined to create one large crack. Figure 4.8 (d) shows the finish coat bulging that occurred at some locations, which made it difficult to measure the crack widths at the door opening corner.
All stucco cracking was evaluated as easily repairable.

**4.3.2 Gypsum Wallboard Damage**

The gypsum wallboard finish sustained little damage after 0.2% [0.34%] drift. Small hairline cracks formed near the corners of the windows and along the edges of the corner bead at some locations. The early stages of joint tape damage was observed as well. Crack widths were only measured when a clearly defined width was obvious. For all other locations, an “HC” denotes the crack widths. “HC” is defined as a visible crack with a width of less than 0.002 in. Figure 4.11 and Figure 4.12 graphically show the wallboard damage after 0.2% [0.34%] drift for Walls 5 to 8 and Figure 4.13 to Figure 4.15 show the typical wallboard damage for Walls 5 to 8. Figure 4.13 (a) shows an initial wallboard crack with some of the joint compound flaking off, and Figure 4.13 (e) shows distributed cracking that occurred at some locations. The same figure also shows the cracks not having an easily defined width due to the latex paint having bulged out. Figure 4.14 (a) shows initial corner bead damage and Figure 4.14 (e) shows the initial finish bulging at the door opening.

**4.4 0.4% Drift**

Wall behavior from 0.2% to 0.4% drift is characterized by some softening of the wall stiffness, extension of cracks in length and width, development of new cracks branching off primary cracks, and no deterioration of wall response during trailing cycles. The wall responses for this stage can be seen in Figure 4.16 and Figure 4.17. For the 0.4% drift cycles, Walls 5 and 7 had a maximum displacement of 0.40 in. and Walls 6 and 8 had a maximum imposed displacements of 0.60 in. and 0.587 in. respectively (identified as [0.6%] in subsequent references and figure captions). The corresponding residual drifts at zero wall force for Walls 5 to 8 were 0.079 in., 0.405 in., 0.0472 in., and 0.177 in. respectively.

The maximum net lateral resistance at 0.4% [0.6%] drift for Walls 5 to 8 is 1,079 lbs/ft, 882 lbs/ft, 993 lbs/ft, and 721 lbs/ft respectively, considering both positive and negative displacement cycles. The average force resisted for Walls 5 to 8 at 0.4% [0.6%] drift was 65% of the average ultimate load of all walls for both the positive and negative displacement cycles.
4.4.1 Portland Cement Plaster Damage

After 0.4% [0.6%] drift, most stucco cracks that developed at 0.2% drift increased in length and width. Figure 4.18 and Figure 4.19 shows the stucco cracking of Walls 5 to 8. New cracks branched from existing cracks and at some locations the cracks propagated to the wall boundaries. The cracks that occurred at the upper window corners propagated vertically toward the wall boundaries at the edges of the solid pier widths. Some stucco cracks formed at the stucco boundaries at wall pier edges and propagated vertically. Figure 4.20 to Figure 4.23 shows typical stucco cracking for Walls 5 to 8. Figure 4.21 (d) and Figure 4.23 (b) are examples of finish coat flaking that occurred at the door opening corners. The stucco cracks that formed at the door opening corners were typically the largest due to the decrease in wall stiffness at that location caused by the large door opening.

4.4.2 Gypsum Wallboard Damage

The gypsum wallboard cracking at all wall opening corners increased in length and width. The wallboard cracks propagated at near 45-degrees from the horizontal. Joint compound flaked off at some locations and fastener popping began at the bottom of the walls, and the joint tape damage that was present at 0.2% drift increased in magnitude. The global wallboard damage for Walls 5 to 8 is shown in Figure 4.24 and Figure 4.25, and the dashed lines indicate corner bead cracking. Figure 4.26 to Figure 4.30 shows the typical wallboard damage after 0.4% drift. Figure 4.26 (c) is an example of the finish flaking and Figure 4.28 shows the cracking of the joint compound over the fastener heads at the wallboard boundaries. Fastener popping initiated at wallboard panel edges and propagated vertically as the displacement level increased. The joint compound over the corner bead began to crack along the length under the windows. Figure 4.29 (a) is an example of the corner bead cracking that was observed.

4.5 0.7% Drift

Wall behavior from 0.4% to 0.7% drift is characterized by softening of the wall stiffness, extension of cracks in length and width, development of new cracks, and very slight deterioration of wall response during trailing cycles. The wall responses for this stage can be seen in Figure 4.31 and Figure 4.32. For the 0.7% drift cycles, Walls 5 and 7 had a maximum displacement of 0.70 in. and Walls 6 and 8 had a maximum imposed
displacements of 0.876 in. and 0.943 in. respectively (identified as [0.9\%] in subsequent references and figure captions). The corresponding residual drifts at zero wall force for Walls 5 to 8 were 0.16 in., 0.579 in., 0.0915 in., and 0.266 in. respectively.

The maximum net lateral resistance at 0.7\% [0.9\%] drift for Walls 5 to 8 is 1,180 lbs/ft, 809 lbs/ft, 1,207 lbs/ft, and 927 lbs/ft respectively, considering both positive and negative displacement cycles. The average force resisted for Walls 5 to 8 at 0.7\% [0.9\%] drift was 87\% of the average ultimate load of all walls for both the positive and negative displacement cycles.

### 4.5.1 Portland Cement Plaster Damage

The stucco damage significantly increased in magnitude from 0.4\% to 0.7\% drift, and the stucco crack widths were relatively large. Figure 4.33 and Figure 4.34 show the stucco cracking for Walls 5 to 8. An “SP” represents locations where the stucco finish coat flaked or spalled from the brown coat. At these locations, it was difficult to make a crack width measurement. Most of the stucco cracks that originated at the wall opening corners propagated to the stucco boundaries at the sill plate, the top plate, and corner studs. More stucco cracks initiated at the stucco boundaries at the wall pier edges, and all existing cracks increased in length and width. Nearly all the primary cracks had new cracks branch off from them and new cracks formed at the top plate stucco boundaries at the stucco pier edges.

Stucco cracks that occurred at the wall opening corners at the edges of the interior stucco piers joined to create one large crack between adjacent wall opening corners and became large in width. Figure 4.35 to Figure 4.38 shows the typical stucco damage for Walls 5 to 8. Figure 4.35 (e) shows a location where partial finish coat spalling at the window opening corner occurred, and Figure 4.36 (d) shows the large stucco crack that occurred above the door opening. This crack was initially present before testing and was large in width at early displacement levels. Figure 4.38 (a), (c), (d), and (e) are all locations where the finish coat spalled off in compression. Small relative stucco panel movement with respect to the wall framing was also noticed at this level of displacement.

### 4.5.2 Gypsum Wallboard Damage

The relative magnitude of damage sustained by the wallboard significantly increased with respect to the minor damage state drift since the gypsum wallboard panels contributed more to the performance of the wall system at higher levels of drift. Because
of the relative stiffness difference between the portland cement plaster and the gypsum wallboard, the stiffer stucco material attracted the majority of the lateral force at small displacement levels. As the stucco deteriorated at the larger displacement levels, the gypsum wallboard attracted more force, which is the reason for the large increase in visual damage between the minor damage state and the moderate damage state drift levels. Figure 4.39 to shows the wallboard damage and crack pattern observed for Walls 5 and 6 after 0.7% [0.9%] drift. An increase in the number of fastener pops was also observed as well as the relative magnitude of joint tape damage.

For Wall 5, Figure 4.41 shows the local wallboard damage observed at the wall opening corners. The corner bead cracks increased in width and were observed to extend the entire length of the corner bead. At compression corners, the gypsum wallboard core crushed, which created distributed cracking or bulging in the wallboard. This effect was more obvious at larger displacement levels. The individual wallboard panels rotated relative to one another, which was evident from the joint tape tearing observed and shown in Figure 4.42. The local wallboard damage that occurred to Wall 6 can be seen in Figure 4.43 and was similar to the damage observed in Wall 5.

4.6 Ultimate Strength

Wall behavior from 0.7% drift up to ultimate strength is characterized by softening of the wall stiffness, extension of cracks in length and width, development of new cracks, and significant deterioration of behavior during trailing cycles. The ultimate net lateral resistance for Walls 5 to 8 is 1,444 lbs/ft, 1,242 lbs/ft, 1,421 lbs/ft, 1,091 lbs/ft which was determined using the maximum forces resisted in each wall. The maximum force of Walls 5 to 8 occurred at 1.40 in., 1.48 in., 1.84 in., and 2.13 in., respectively. The wall response can be seen in Figure 4.46 and Figure 4.47.

4.7 Failure

4.7.1 Measured Response

Global Response

The global wall response of the walls at failure can be seen in Figure 4.48 and Figure 4.49 for Walls 5 & 6 and Walls 7 & 8, respectively. A comparison of the primary cycles and subsequent trailing cycle backbone curves shows virtually no deterioration in the walls for the trailing cycles shown in Figure 4.50 and Figure 4.51. The trailing cycles
nearly mirror each other and are shown as dashed and dotted lines.

As may be seen in Figure 4.52, the presence of fiber reinforcement in the stucco does not significantly affect the structural performance of the walls.

**Anchorage Uplift Force**

The locations of the anchorage forces is covered in Chapter 2, and the same convention is to be used for the remainder of the report. Figure 4.53 and Figure 4.55 show the measured anchor bolt uplift forces at varying levels of drift the positive and negative displacement cycles measured for Walls 5 and 6. The anchorage force load cell for location 1 was damaged and is not reported. The anchor bolts closest to the ends of the wall are shown since the largest forces were measured at these locations.

The trend for both walls shows that the anchor bolt forces continually increase up to a drift level of 1.5%, then decrease as the wall displacement increases. This is caused by the different displacement mechanisms of the wall at different levels of drift. At lower drift levels, the walls rock more or less as a rigid body. The increase in overturning created an increase in anchorage force with increased wall displacements. Once the wall stiffness began to degrade, the damage was concentrated in other forms such as increased finish damage or damage at the sill plate level. Damage at the sill plate level inhibits the lateral force transfer to the anchor connections, thus lowering the developed force. The structure dead load, sill and stud uplift, and wall rotations and shear deformations all influence the development of anchor bolt uplift forces.

**Wall Pier Rotation**

Inclinometers were placed at the mid-height of the wall piers at the wall mid-height to measure any rigid body rotation of the individual stucco wall piers. Chapter 2 discusses the locations of the inclinometers along the length of the walls. When the stucco panels rotated, the force distribution to the nails was more evenly distributed to the furring nails connecting the stucco to the framing. When the wall framing began to deform more in shear and rotate less, the forces were concentrated at wall boundaries, either the top plate or the sill plate. This created a larger force demand on the nailing at the sill plate level. If the amount of nailing to the sill could not adequately resist the developed forces, the nailing of the stucco to the sill plate failed and the stucco panels displaced relative to the framing.
Figure 4.57 to Figure 4.60 show the individual stucco wall pier rotations measured along the wall at different levels of drift. From the measured rotation data for Phase I of the project and from geometric symmetry, the two window wall configuration rotations were measured for half of the wall. For the positive and negative displacement cycles, the main wall piers rotated more than the sections above or below any wall openings which was consistent for both wall specimen configurations. This difference became more pronounced at large displacement levels. All of the main wall pier rotations were similar in magnitude with the exception of the wall pier adjacent to the door opening for Wall 6. The slender stucco wall pier next to the door opening had a much larger rotations compared to all other wall piers. This can be attributed to the inherent flexibility of the wall having a door opening introduced close to the end of the specimen. Large stucco cracks formed at the upper left hand corner (stucco elevation view) of the door opening at wall displacements of 0.7% and greater. The large stucco cracks at this location allowed the wall end pier to rotate significantly more than the other wall piers at large displacement levels.

*Stud Uplift*

Stud uplift was another displacement mechanism that was directly measured and represents the displacement between the top of the sill plate and the bottom of the studs. Figure 4.61 shows the stud uplift calculated by subtracting the measured sill plate uplift from the stud uplift since both quantities were referenced from the testing frame. For Wall 5, Stud 1 refers to the corner stud at the northern end of the wall and Stud 2 refers to the corner stud at the southern end of the wall. Stud 1 uplifts during the negative displacement cycles, and Stud 2 uplifts during the positive displacement cycles. The uplift for Stud 2 is consistently larger than the uplift for Stud 1, which can be attributed to the spacing of the anchor bolts. The sill plate at the southern end of the wall is more restrained by the presence of an anchor bolt being closer to the end of the wall than the opposite end. The total uplift at both wall ends was observed to be very close in magnitude and the sill plate uplift varied.

Wall 6 displayed similar behavior as Stud 1 uplift was consistently larger than any other measured location. At displacement levels of 1.5% and higher, the wall behaves as two separate sections divided by the door opening. This was evident from the large stucco cracking at the door opening and the similar stud uplifts measured for each
individual wall section.

Stucco Separation

The separation of the stucco cladding from the structural framing was measured at two locations above the sill plate along the length of each test specimen (see Figure 2.26, Table 2.14, and Table 2.15.) Figure 4.63 shows the stucco separation for Wall 5. The stucco separated more at the end, which experienced uplift for the positive displacement cycles and no clear trend was observed for the negative displacement cycles. Figure 4.64 it can be seen that the location of the greatest stucco separation always occurred at the location near the door opening for both the positive and negative displacement cycles.

Longitudinal Stucco Movement

The stucco movement relative to the framing was calculated by subtracting the measured sill plate movement from the measured stucco movement and is shown in Figure 4.68. As the displacements increased, the stucco movement increased for all displacement levels for both specimens. For Wall 5 the positive displacement cycles consistently had more stucco movement compared to the negative displacement cycles, which may be attributed to some softening of the connection in the primary direction creating larger movement in the negative direction, however Wall 6 exhibited the opposite behavior.

Shear Deformation

String potentiometers were used to measure the shear deformation of each wall panel and the deformation contributing to the global wall displacement was calculated and shown in Figure 4.70 and Figure 4.71. For Walls 5 and 6, the shear deformation contributes less to the overall deformation mechanism of the wall as the wall displacements increase. The stud uplift and wall rotations begin to contribute more to the total deformation.

Equivalent Viscous Damping

A measure of the amount of energy dissipated by the test specimens was also checked so that the equivalent viscous damping at various levels of drift could be observed. The most common method for defining equivalent viscous damping is to equate the energy dissipated in one of the hysteresis loops from testing and an equivalent viscous system. The energy dissipated in the walls is given by the area enclosed by the
hysteresis loop \((E_D)\). The dissipated energy and the energy dissipated in viscous damping were equated to determine the equivalent viscous damping ratio \(\xi_{eq}\). The definition of terms is shown in Figure 4.74 and from Figure 4.75 it can be seen that the equivalent viscous damping ratio is near 20% for most cases.

### 4.7.2 Portland Cement Plaster Damage

The stucco cracking patterns for both wall specimens at failure can be seen in Figure 4.77. Large crack widths that formed at wall opening corners and propagated to the panel boundaries produced individual stucco sections that rotated independently of one another. Figure 4.79 shows an exaggerated version of the measured stucco section rotations assuming rigid body rotation and neglecting all other deformation mechanisms for clarity. The cracking patterns observed follow the expected damage patterns for a wall with openings and the local stucco damage for Wall 5 is shown in Figure 4.83 and the local cracking for Wall 6 is shown in Figure 4.84. Spalling of the stucco finish coat followed by crumbling of the brown and scratch coats at failure occurred at all opening corner locations at large displacement levels.

Figure 4.80 shows the observed sill uplift at +2.5% drift (a) along the sill plate and (b) shows the corner stud uplift at the wall end. The corner studs twisted at the wall ends, which created vertical cracking in the stucco along the corner rite reinforcement, causing the stucco to eventually deteriorate as seen in Figure 4.81. The corner stud twisting occurred due to the eccentricity created by the difference in the strengths associated with the interior and exterior finish materials.

### 4.7.3 Gypsum Wallboard Damage

The crack pattern and wallboard damage observed at failure is shown in Figure 4.88. Most of the wallboard joints were significantly damaged when the individual wallboard piers rotated relative to one another. Large crack widths and lengths were observed at all wall opening corners, and the cracks tended to follow a 45-degree path. The only deviation from 45 degrees was noticed at wall corners adjacent to a horizontal wallboard joint. For this case, the cracks began to level out horizontally and the majority of the damage was concentrated in the wallboard joints rather than at the wall opening corners. At wall returns, some ridging of the wallboard also occurred at large displacements and eventually resulted in large cracks. This occurred since the wallboard
rotation was restricted at the wall returns unless the corner studs significantly deformed.

The gypsum wallboard damage for Wall 5 after 2.5% drift can be seen in Figure 4.94. Figure 4.92 shows the individual wallboard rotations evident by the separation of the corner bead and the wallboard joint compound. Figure 4.95 shows the joint tape damage that occurred after 2.5% drift. All wallboard joints for Wall 5 sustained significant damage. Figure 4.97 shows the localized wallboard damage sustained by Wall 6 and Figure 4.96 shows the observed fastener popping. As the wall displacement increased, the fastener popping became more obvious and were concentrated at the lower half of the walls. Figure 4.90 shows the deformation of the doorframe at +2.0% drift.

4.7.4 Observed Damage after Finish Removal

Once the testing of the walls was completed, various sections of the stucco were removed to investigate the condition of the building paper and lath. Figure 4.104, Figure 4.105, and Figure 4.106 show locations where the stucco was removed and it can be seen that the lath did not fracture at any of the opening corner locations, but building paper tearing did occur at some locations. It is unknown at what level of drift the tears began, however given the relative stiffness of the stucco and the building paper, tearing would not be expected at lower drift levels. For Walls 1 and 2 tested in Phase I, tearing of the building paper at the corners of openings was not observed at 1.5% drift. Figure 4.107 shows locations where the gypsum wallboard was removed and the condition of the framing was inspected. Building paper tearing also occurred where the stucco moved relative to the framing and was torn by the furring nails. The furring nails were also observed to pull out of the studs at locations where sufficient edge clearance was not attained into the stud. The relative magnitude of stucco separation from the framing is also shown.
Figure 4.1 Global Response of Walls 5 and 6 for 0.2% [0.34%] Drift
Figure 4.2 Global Response of Walls 7 and 8 for 0.2% [0.34%] Drift
Figure 4.3 Walls 5 and 6 Stucco Cracking after 0.2% [0.34%] Drift
Figure 4.4  Walls 7 and 8 Stucco Cracking after 0.2% [0.34%] Drift
Figure 4.5 Wall 5 Stucco Cracking after 0.2% Drift (North Window)
Figure 4.6 Wall 5 Stucco Cracking after 0.2% Drift (South Window)

Figure 4.7 Wall 5 Stucco Cracking after 0.2% Drift (Central Pier)
Figure 4.8 Wall 6 Stucco Cracking after 0.2% [0.34%] Drift
Figure 4.9 Wall 7 Stucco Cracking after 0.2% Drift
Figure 4.10  Wall 8 Stucco Cracking after 0.2% [0.34%] Drift
Figure 4.11  Walls 5 and 6 Wallboard Damage after 0.2% [0.34%] Drift
Figure 4.12  Walls 7 and 8 Wallboard Damage after 0.2% [0.34%] Drift
Figure 4.13 Wall 5 Wallboard Damage after 0.2% Drift
Figure 4.14 Wall 6 Wallboard Damage after 0.2% [0.34%] Drift
Figure 4.15  Wall 8 Wallboard Damage after 0.2% [0.34%] Drift
Figure 4.16 Global Response of Walls 5 and 6 for 0.4% [0.6%] Drift
Figure 4.17 Global Response of Walls 7 and 8 for 0.4% [0.6%] Drift
Figure 4.18 Walls 5 and 6 Stucco Cracking after 0.4% [0.6%] Drift
Figure 4.19 Walls 7 and 8 Stucco Cracking after 0.4% [0.6%] Drift
Figure 4.20  Wall 5 Stucco Cracking after 0.4% Drift
Figure 4.21  Wall 6 Stucco Cracking after 0.4% [0.6%] Drift
Figure 4.22  Wall 7 Stucco Cracking after 0.4% Drift

Figure 4.23  Wall 8 Stucco Cracking after 0.4% [0.6%] Drift
(a) Wall 5

(b) Wall 6

Figure 4.24 Walls 5 and 6 Wallboard Damage after 0.4% [0.6%] Drift
Joint tape tearing

(a) Wall 7

Joint tape tearing

(b) Wall 8

Figure 4.25  Walls 7 and 8 Wallboard Damage after 0.4% [0.6%] Drift
Figure 4.27 Wall 6 Wallboard Damage after 0.4% [0.6%] Drift

Figure 4.28 Wall 6 Wallboard Fastener Popping after 0.4% [0.6%] Drift
Figure 4.29  Wall 7 Wallboard Damage after 0.4% Drift

Figure 4.30  Wall 8 Wallboard Damage after 0.4% [0.6%] Drift
Figure 4.31  Global Response of Walls 5 and 6 for 0.7% [0.9%] Drift
Figure 4.32 Global Response of Walls 7 and 8 for 0.7\% [0.9\%] Drift
Figure 4.33 Walls 5 and 6 Stucco Cracking for 0.7% [0.9%] Drift
Figure 4.34 Stucco Cracking for 0.7% [0.9%] Drift
Figure 4.35 Wall 5 Stucco Cracking for 0.7% Drift
Figure 4.36  Wall 6 Stucco Damage for 0.7% [0.9%] Drift
Figure 4.37 Wall 7 Stucco Damage for 0.7% Drift
Figure 4.38 Wall 8 Stucco Damage for 0.7% [0.9%] Drift
Figure 4.39 Wallboard Damage for 0.7% [0.9%] Drift
Figure 4.40 Wallboard Damage for 0.7% [0.9%] Drift
Figure 4.41 Wall 5 Wallboard Damage for 0.7% Drift
Figure 4.42  Wall 5 Joint Tape Tearing for 0.7% Drift
Figure 4.43  Wall 6 Wallboard Damage for 0.7% [0.9%] Drift
Figure 4.44  Wall 7 Wallboard Damage for 0.7% Drift
Figure 4.45  Wall 8 Wallboard Damage for 0.7% [0.9%] Drift
Figure 4.46  Global Response of Walls 5 and 6 at Ultimate Strength
Figure 4.47 Global Response of Walls 7 and 8 at Ultimate Strength
Figure 4.48 Global Response of Walls 5 and 6 to Failure
Figure 4.49 Global Response of Walls 7 and 8 to Failure
Figure 4.50  Backbone Curves of Walls 5 and 6 with Trailing Cycles
Figure 4.51  Backbone Curves of Walls 7 and 8 with Trailing Cycles
Figure 4.52 Comparison of Wall Strength with and without Chop Strand Fibers

(a) Walls 5 and 7

(b) Walls 6 and 8
(a) Positive Displacement Cycles

Figure 4.53  Wall 5 Anchorage Uplift Forces
Figure 4.54  Wall 7 Anchorage Uplift Forces

(a) Positive Displacement Cycles

(b) Negative Displacement Cycles
Figure 4.55  Wall 6 Anchorage Uplift Forces

(a) Positive Displacement Cycles

(b) Negative Displacement Cycles
Figure 4.56 Wall 8 Anchorage Uplift Forces
Figure 4.57  Wall 5 Pier Rotations
Figure 4.58  Wall 6 Pier Rotations
Figure 4.59  Wall 7 Pier Rotations
Figure 4.60 Wall 8 Pier Rotations
Figure 4.61 Stud Uplift of Walls 5 and 6
Figure 4.62  Stud Uplift for Walls 7 and 8
Figure 4.63  Wall 5 Stucco Separation at Sill Plate
Figure 4.64  Wall 6 Stucco Separation at Sill Plate
Figure 4.65 Wall 7 Stucco Separation at Sill Plate
Figure 4.66 Wall 8 Stucco Separation at Sill Plate
Figure 4.67  Average Stucco Separation from Framing at Sill Plate
Figure 4.68  Stucco Movement Relative to Framing for Walls 5 and 6
Figure 4.69  Stucco Movement Relative to Framing for Walls 7 and 8
Figure 4.70 Wall 5 Shear Deformation
Figure 4.71  Wall 6 Shear Deformation
Figure 4.72  Wall 7 Shear Deformation
Figure 4.73  Wall 8 Shear Deformation
Deformation

\[ k = \frac{F}{u} \]

\[ E_s = \frac{k}{2} \frac{u_o^2}{\zeta} \]

\[ \zeta = \frac{1}{4\pi} \frac{E_D}{E_s} \]

Figure 4.74 Definition of Equivalent Viscous Damping

Figure 4.75 Equivalent Viscous Damping of Walls 5 and 6
Figure 4.76 Equivalent Viscous Damping of Walls 7 and 8
Figure 4.77  Stucco Damage at Failure
Figure 4.78  Stucco Damage at Failure
Figure 4.79  Relative Individual Wall Section Rotations
(a) Uplift at +2.5% Drift  
(b) Uplift at +2.5% Drift

Figure 4.80 Wall 5 Sill Uplift

Figure 4.81 Wall 6 Corner Stud Twisting at Failure
(a) Wall 7 Uplift at +2.0% Drift

(b) Wall 7 Uplift at –2.0% Drift

(c) Wall 8 Uplift at –2.0% Drift

Figure 4.82 Sill Uplift at 2% Drift
Figure 4.83  Wall 5 Stucco Damage at Failure
Figure 4.84  Wall 6 Stucco Damage at Failure
Figure 4.85  Wall 7 Stucco Damage at Failure
Figure 4.86 Wall 7 Stucco Damage at Failure
Figure 4.87 Wall 8 Stucco Damage at Failure
Major joint tape tearing

(a) Wall 5

Major joint tape tearing

(b) Wall 6

Figure 4.88 Wallboard Damage at Failure
Figure 4.89 Wallboard Damage at Failure
Figure 4.90  Wall 6 Door Jamb Deformation at +2.0% Drift

Figure 4.91  Wall 8 Door Shear Deformation at +2.0% Drift
Figure 4.92  Wall 5 Wallboard Rotation at +2.0% Drift

(a)  +2.0% Drift  (b)  -2.0% Drift

Figure 4.93  Wall 7 Wallboard Rotation at 2% Drift
Figure 4.94  Wall 5 Wallboard Damage at Failure
Figure 4.95  Wall 5 Joint Tape Tearing at Failure

Figure 4.96  Wall 6 Wallboard Fastener Popping
Figure 4.97  Wall 6 Wallboard Damage at Failure
Figure 4.98  Wall 7 Wallboard Damage at Failure
Figure 4.99  Wall 7 Wallboard Damage at Failure

Figure 4.100  Wall 7 Joint Tape Tearing
Figure 4.101  Wall 8 Wallboard Damage at Failure
Figure 4.102  Wall 8 Fastener Popping at Failure

Figure 4.103  Wall 8 Wallboard Buckling at Failure
Figure 4.104  Wall 5 Stucco Removal after Testing
Figure 4.105  Wall 6 Stucco Removal after Testing
Figure 4.106  Walls 7 and 8 after Stucco Removal
(a) Building paper tearing  
(b) Furring nail pulling out of studs  
(c) Stucco separation  
(d) Stucco separation  

Figure 4.107 Framing Inspection after Wallboard Removal after Testing
(a) Wall 7 Stucco Separation

(b) Wall 8 Separation of Stucco and Building Paper Tearing

Figure 4.108 Walls 7 and 8 with Wallboard Removed
Chapter 5  Testing of Walls 9 and 10

5.1  Introduction

Before proper testing of Walls 9 and 10 was performed, the walls were destroyed by a laboratory accident. While hooking up the actuator to the wall specimens, the hydraulic controls malfunctioned and sent a pulse to the actuator, which effectively moved both wall specimens through roughly 8 in. of displacement within 1/2 of a second. The walls were completely destroyed from this pulse and all observed damage was documented. The data acquisition system was on and the instrumentation did record during that time, but the data that was recorded was difficult to decipher and much of the data was not useful.

The actuator pulse can be compared to an intense seismic pulse common in near-fault ground motions, however without smaller cyclic activity of a time history representing the smaller accelerations. Since the pulse was unidirectional, all phenomena relative to the displacement in one direction was gathered and reported in this chapter. All documented damage was reported with the walls in a permanently displaced position.

5.2  Documented Damage of Walls 9 and 10

5.2.1  Portland Cement Plaster Damage

The magnitude of damage to the stucco cladding was far greater than seen in previous testing, but the general damage and crack patterns were similar. Figure 5.1 shows the general crack patterns in the stucco and from viewing the direction of cracking, it becomes obvious which direction the displacement occurred since the majority of the cracking occurred at tension corners.

At wall opening compression corners, the stucco cracking was limited to one or two main cracks and some spalling of the finish coat from the brown coat. At wall opening tension corners, a large number of stucco cracks formed as expected due to the large difference in the performance of stucco in compression versus tension. Figure 5.2 (a) and (b) show the difference in observed stucco cracking between a compression corner and a tension corner for Wall 9. Figure 5.2 (c) shows the central pier of Wall 9 and it can be seen that the walls still crack in a manner that breaks the stucco into
individual wall pier sections and rotate independent of one another. Figure 5.3 shows the magnitude of uplift that was observed at one end of Wall 9. Figure 5.4 (a) shows the stucco cracking that occurred at a tension corner for Wall 10, and Figure 5.4 (b) shows the global view of the damage sustained by Wall 10.

All the windows were significantly deformed and all fixed pane windows shattered. The window frames were also observed to buckle. From Figure 5.5 the shear deformation that occurred to the doorframe can be seen. From Figure 5.6 the magnitude of framing movement relative to the sill plate can be seen, and Figure 5.7 shows the uplift of Wall 10. The significant movement of framing relative to the sill plate occurred as the stucco separated from the framing and the shear force could no longer be effectively transferred through the stucco/sill plate connection resulting in the shear force at the base of the studs being too great for the two face-nailed 16d nails per stud to adequately resist. The nails can be seen to lie flat as if bent straight down.

5.2.2 Gypsum Wallboard Damage

The observed damage that occurred to the gypsum wallboard was slightly different than previously observed in the previous tests, but the global pattern was again consistent with what was expected. Figure 5.8 shows the damage patterns that occurred to the gypsum wallboard and the wallboard joints that experienced damage are circled. The main difference between the cyclic tests was the lack of joint tape tearing for both walls. Large cracks and wallboard buckling were all consistent with what was previously observed in the previous testing.

Figure 5.9 (a) shows the central pier where the cracks that formed at window corners converged. The difference between a compression corner and a tension corner can be easily seen as the tension corner has a very large open crack and gypsum core at the compression corner has crushed and bulged out. Figure 5.10 (a) shows a global view of the wallboard damage sustained by Wall 10. Figure 5.10 (b) and (c) show the shear deformation of one of the windows and door respectively. Figure 5.11 shows the wallboard buckling of Wall 10 and Figure 5.12 shows the wall movement relative to the sill plate.

Portions of the wall finishes were removed so that the building paper, the wire lath, and nail deformations could all be investigated. Because of the unidirectional pulse, the nail deformations were much cleaner and more obvious to see compared to a cyclic
test. Figure 5.13 (a) to (d) shows locations before and after the removal of the stucco. Tearing of the building paper was observed at all tension corner locations, but no lath fracture was observed at most locations even when the width of stucco cracks was in excess of 5/8 in. Figure 5.13 (e) shows the observed lath buckling that occurred in Wall 10 as two separate stucco sections moved relative to one another. From the typical deformation pattern of a shear wall, the expected direction of nail deformation is predicted. Assuming rigid body rotation of sections of the finish or sheathing coupled with the shear deformation of the pinned framing members, the general direction of the resultant and the expected nail deformations is shown in Figure 5.14 (uplift was not shown for this case). Figure 5.15 shows the typical deformation of the individual stucco sections as observed from previous testing. The expected furring nail deformations and the actual nail deformations observed are similar and shown in Figure 5.16. Figure 5.17 shows the nail deformations of the cooler nails and the nail deformations are in the opposite direction of the furring nail deformations. This is due to the large difference in the relative stiffness of the stucco versus the wallboard. The stucco rotated significantly more than the gypsum wallboard, evident by the lack of joint tape damage for such large displacements. Figure 5.18 shows the magnitude of movement of the framing relative to the sill plate.
Figure 5.1 Stucco Damage of Walls 9 and 10
Figure 5.2  Wall 9 Stucco Damage
Figure 5.3  Wall 9 Uplift at South End of Wall

(a) Tension corner

(b) Global view

Figure 5.4  Wall 10 Stucco Damage
Figure 5.5 Wall 10 Stucco Damage at Door Opening

Figure 5.6 Wall 10 Movement Relative to Sill Plate

Figure 5.7 Wall 10 Uplift at South End of Wall
Figure 5.8  Wallboard Damage of Walls 9 and 10
Figure 5.9 Wall 9 Gypsum Wallboard Damage

(a) Central pier

(b) Compression corner

(c) Compression corner
(a) Global view

(b) Window shear deformation

(c) Door shear deformation

Figure 5.10 Wall 10 Gypsum Wallboard Damage
Figure 5.11  Wall 10 Gypsum Wallboard Buckling

Figure 5.12  Wall 10 Wall Movement Relative to Sill Plate

Stud pull out from sill face nailing
Figure 5.13 Building Paper and Lath Inspection
Figure 5.14  Typical Shearwall Nailing Forces

Figure 5.15  Typical Deformation Pattern of One-Window Wall Configuration
Figure 5.16  Wall 10 Furring Nail Deformation

Figure 5.17  Wall 10 Gypsum Wallboard Cooler Nail Deformation
Figure 5.18  Wall 10 Stud Pullout from Sill Plate

(a) After finish removal

(b) After finish removal
Chapter 6  Cyclic Behavior of Walls 11 and 12: Stages 1 and 2

6.1 Introduction

For Walls 11 and 12, a 6 in. concrete stem wall was constructed in the testing frame so that the stucco could be extended past the bottom of the sill plate onto the concrete. This style of construction was typical of the plastering process prior to the 1970s. The practice of extending the stucco past the bottom of the sill plate inhibited a proper escape route for trapped moisture from behind the wall, thus causing the sill plate to decay and it also created a location prone to horizontal stucco cracking.

Due to the hydraulic accident that occurred during Test 3 (Walls 9 and 10, see Chapter 5), the testing of Wall specimens 11 and 12 was conducted in two separate stages. For Stage 1, the walls were tested up to 0.4% drift, replumbed, and both the stucco and drywall were repaired. For Stage 2, the walls were loaded to failure from the beginning of the loading protocol.

6.2 0.2% Drift

Wall behavior up to 0.2% drift is characterized by a very stiff, nearly linear elastic response with minor cracking of finishes and no deterioration of behavior during trailing cycles. The global response up to this level can be seen in Figure 6.1. For the 0.2% drift cycles, Walls 11 and 12 had maximum displacements of 0.20 in. and 0.29 in, respectively (identified as [0.29%] in subsequent references and figure captions). The corresponding residual drifts at zero wall force for Walls 11 and 12 were 0.087 in. and 0.116 in. respectively.

The maximum net lateral resistance at 0.2% [0.29%] drift for Walls 11 and 12 is 1,313 lbs/ft and 1,133 lbs/ft respectively, considering both positive and negative displacement cycles. The average force resisted for Walls 11 and 12 at 0.2% [0.29%] drift was near 72% of the average ultimate load of both walls for both the positive and negative displacement cycles.

6.2.1 Portland Cement Plaster Damage

Figure 6.2 shows the global stucco crack pattern for 0.2% drift for Walls 11 and 12. The typical stucco cracks for Walls 11 and 12 can be seen in Figure 6.3 to Figure 6.5.
Contrary to Wall 11, Wall 12 had a door opening, which interrupted the continuous stucco connection at the sill plate level between the stucco above and below the sill plate. This caused the stucco connection at the bottom of the sill plate for Wall 12 to fail at a smaller displacement level than Wall 11 because of a smaller cross-sectional area present to resist the developed shear forces at the sill plate. Once the connection at the sill plate level was fractured, the wall could more easily rotate and uplift. Because the testing was conducted under displacement control of Wall 11, Wall 12 displaced nearly twice that of Wall 11 once the connection at the sill plate failed during the 0.2% drift cycles.

Small hairline cracks formed at the sill plate level of Wall 12 during the 0.1% drift cycles. The connection failed between 0.1%-0.2% drift cycles (actual drift of 0.13%-0.38%), however Wall 11 had very little cracking at the sill plate level up to 0.2% drift. Figure 6.6 shows the magnitude of sill cracking for Wall 12 and Figure 6.7 shows the sill cracking for Wall 11. Figure 6.8 shows the stucco cracking at zero wall force for Wall 12. Wall 11 stucco cracking at the sill plate was very small.

6.2.2 Gypsum Wallboard Damage

Because the stucco attracted the majority of the force at the small displacement cycles, the damage to the gypsum wallboard was minimal. Figure 6.9 shows the global wallboard damage pattern for Walls 11 and 12. Some joint tape tearing occurred in Wall 11 as well as some minor corner bead cracking. Figure 6.10 to Figure 6.12 shows the typical wallboard cracks at the wall opening corners, and it can be seen that no definite crack width was easily distinguishable. No crack widths were measured, but obvious wallboard stress was observed with the most obvious damage occurring at the door opening corners.

6.3 0.4% Drift

Wall behavior from 0.2% to 0.4% drift is characterized by some softening of the wall stiffness, extension of cracks in length and width, development of new cracks branching off primary cracks, and no deterioration of wall response during trailing cycles. The global response up to this level can be seen in Figure 6.13. For the 0.4% drift cycles, Walls 11 and 12 had maximum displacements of 0.40 in. and 0.78 in, respectively (identified as [0.78%] in subsequent references and figure captions). The corresponding residual drifts at zero wall force for Walls 11 and 12 were 0.219 in. and 0.137 in.
The maximum net lateral resistance at 0.4% drift for Walls 11 and 12 is 1,428 lbs/ft and 1,226 lbs/ft respectively, considering both positive and negative displacement cycles. The average force resisted for Walls 11 and 12 at 0.4% drift was near 87% of the average ultimate load of both walls for both the positive and negative displacement cycles.

**6.3.1 Portland Cement Plaster Damage**

All primary stucco cracks at the wall opening corners increased in width. New cracks branched from existing cracks at some locations, and most stucco cracks at the opening corners propagated toward the stucco boundaries. The finish coat spalled from the stucco basecoat of Wall 12. Figure 6.14 shows the stucco crack pattern for Walls 11 and 12 after the 0.4% [0.78%] drift cycles (The number in brackets in the figure represents the stucco crack width after the walls were returned to the zero displacement position before the walls were repaired). Figure 6.15 shows the stucco crushing and sill uplift that was observed during the positive displacement drift cycles for Wall 12, and Figure 6.16 shows the stucco uplift that occurred during the negative displacement cycles. At this displacement, the stucco above the sill plate was observed to have displaced nearly 1/4 in. relative to the stucco attached to the stemwall for Wall 12, which can be seen in Figure 6.15 (b). Figure 6.17 to Figure 6.19 shows the typical stucco cracks at wall opening corners. Figure 6.19 (f) shows the finish coat spalling of Wall 12 at the door opening. During the 0.4% [0.78%] drift cycles, Wall 12 displaced over twice the control displacement of Wall 11, which is the primary reason for the difference in the magnitude of damage observed for Walls 11 and 12.

The stucco cracking at the sill plate significantly increased in magnitude for Wall 11 from 0.2% drift to 0.4% drift. The crack nearly extended the length of the wall and is shown at +0.4% drift in Figure 6.20. Wall 12 stucco cracking at the sill plate was extensive for the 0.4% [0.78%] displacement cycles. The cracks extended the full length of the wall and crushing and spalling of the finish coat occurred as the stucco above the sill plate moved relative to the stucco below the sill plate. Figure 6.21 shows the crack at the positive peak of the 0.4% [0.78%] drift cycles for Wall 12. Figure 6.22 shows the sill crack for Wall 11 at zero wall force, and Figure 6.23 shows the sill crack of Wall 12 at zero wall force.
6.3.2 Gypsum Wallboard Damage

The gypsum wallboard cracking slightly increased from the 0.2% [0.29%] drift cycles for both walls. Joint tape tearing became more prevalent along with corner bead finish cracking and some fastener popping originating at the wallboard boundaries. Figure 6.24 shows the general wallboard damage observed for Walls 11 and 12, and Figure 6.25 to Figure 6.27 shows typical local damage at wall opening corners. The wallboard damage sustained by Wall 11 did not require the replacement of any sections of wallboard, and the damage could be readily repaired using conventional methods. Since Wall 12 displaced over twice that of Wall 11, the damage was more extensive and the wallboard at the door opening corners required replacing.

6.4 Measured Response: Stage 1

Global Response

Walls 11 and 12 attracted more force at equivalent displacement levels when compared to Walls 5 through 8. A plot of the backbone curves of Walls 5 and 6 versus Walls 11 and 12 is shown in Figure 6.28. The backbone curves for Walls 7 and 8 are nearly the same as the backbone curves for Walls 5 and 6 and therefore not compared. The larger attraction of force created more stucco cracks at the same displacement levels because of the larger force demand on the stucco diaphragm. The attachment of the stucco to the concrete stemwall was the primary cause of the increase in the stiffness of the Walls 11 and 12. The stucco diaphragm above the sill plate was no longer allowed to freely rotate and uplift because of the stucco below the sill plate. Because the stucco rotation and uplift at small displacements contributes to the wall displacement mechanism, more force was required to move the walls an equivalent displacement if the stucco was free to rotate and uplift.

Figure 6.29 shows the global force deformation response of Walls 11 and 12. The stucco at the sill line for Wall 11 was intact at 0.4% [0.78%] drift, but had failed in a brittle fashion for Wall 12 and its stiffness began to significantly degrade. The sliding of the stucco sections above the sill plate relative to those below created a “stick-slip” type response coupled with instrumentation noise is reflected in the jagged response of the force-deformations curves. Figure 6.30 shows the net lateral resistance of the walls specimens in the positive direction of loading which is the primary direction. The values
were calculated at the specified drift level, subtracting the length of the wall openings.

**Anchorage Uplift Forces**

Figure 6.31 shows the measured anchorage uplift forces for each drift level. The load cell at location 4 for Wall 11 was damaged and no data was recorded.

**Wall Pier Rotation**

Figure 6.32 and Figure 6.33 shows the wall pier rotations for Walls 11 and 12, and the trends were consistent with previous testing.

**Stud Uplift**

Figure 6.34 shows the measured stud uplift.

### 6.5 Wall Rehabilitation

After the walls were cycled through 0.4% [0.78%] drift, the walls were returned to zero displacement. Various common repair methods were used to rehabilitate the stucco and the gypsum wallboard finishes with the exception of one location where an innovative repair method was used.4

#### 6.5.1 Portland Cement Plaster

For the repair of the stucco, the California Plastering Consultants specification was used to repair any cracks. Deck screws were also installed in the stucco at the sill plate to inhibit any stucco separation or movement relative to the framing. Table 6.1 shows the steps involved for each repair method and Figure 6.35 shows the locations where the repair was used.

The California Plastering Consultants specification was used on the largest visible cracks at all wall opening locations. The cracks were routed out with a diamond grinder and the finish coat was ground down to the brown coat. An acrylic bonder was applied along the length of the crack and where any of the finish was removed. A fiberglass tape was then applied along the crack. A cementitious material called “dry bond” was applied over the fiberglass tape. The repair was completed by the addition of a smooth finish coat and paint. The stucco repair process is shown in Figure 6.36 to Figure 6.41. Figure 6.42 shows the repair of the horizontal crack that occurred at the sill plate and Figure 6.43

4 Note that the objective of the testing was to evaluate the performance of the repairs during subsequent reloading of the wall. No effort was made during repairs to match the appearance of the stucco finish, although such matching is possible with the techniques employed.
shows the installation of the 2-1/2 in. screws into the sill plate.

6.5.2 Gypsum Wallboard

The methods used to repair any gypsum wallboard damage are shown in Table 6.2 and the locations where each method was used is shown in Figure 6.44. All cracks in the wallboard finish were routed out (see Figure 6.45) and were finished over with joint compound or had either fiberglass or paper tape placed over any cracks and finished over. For locations where any joint tape tearing was observed, the damaged tape was stripped and replaced with fiberglass tape or paper tape and refinished (see Figure 6.46). All fastener pops were reset and repaired by installing an additional cooler nail at 1 in. from the damaged fastener (see Figure 6.47).

Gypsum wallboard manufacturers don’t recommend having vertical wallboard joints at the corners of wall openings, however repair method 6 involved removing any excessively damaged wallboard and installing a vertical joint at that location in an effort to limit the wallboard damage to a specific location. Figure 6.48 shows the various steps involved. The damaged sections were removed and replaced, leaving a 1/8 in. gap above the door opening where the vertical joint was created. “L” molding was used and the gap was filled with elastic caulking. The repair was then finished over and painted.

6.6 Observed Damage: Stage 2

Once the wall repairs were completed and allowed to cure for one week, the walls were retested. Stage 2 testing began from zero load and displacement and followed the loading protocol until failure of both walls was achieved. The general global behavior of the walls was similar to Stage 1 up through the 0.4% drift cycles.

6.7 0.2% Drift

Wall behavior up to 0.2% drift is characterized by a very stiff, nearly linear elastic response with minor cracking of finishes and no deterioration of behavior during trailing cycles. The global response for this level of drift for Stage 2 testing is shown in Figure 6.49. For the 0.2% drift cycles, Walls 11 and 12 had maximum displacements of 0.20 in. and 0.364 in, respectively (identified as [0.36%] in subsequent references and figure captions). The corresponding residual drifts at zero wall force for Walls 11 and 12 were 0.090 in. and 0.108 in. respectively.

The maximum net lateral resistance at 0.2% drift for Walls 11 and 12 is 834 lbs/ft
and 891 lbs/ft respectively, considering both positive and negative displacement cycles. The average force resisted for Walls 11 and 12 at 0.2% drift was near 53% of the average ultimate load of both walls for both the positive and negative displacement cycles.

6.7.1 Portland Cement Plaster Damage

The performance of the stucco for the repaired walls was similar to the original walls at the same level of drift, with some small local variation. The global stucco cracking patterns is shown in Figure 6.50 and Figure 6.51 to Figure 6.52 shows the local damage at the wall opening corners and at the sill plate. Any observed stucco cracks generally occurred within the repair area, and any cracks that were painted over were visible at some locations. Some bulging of the fiberglass tape and finish coat occurred at some locations and the repaired horizontal cracking at the sill plate level was essentially repeated and cracked along the full length of the original crack.

6.7.2 Gypsum Wallboard Damage

A pastel base interior latex paint was used to repaint the gypsum wallboard after the repairs were made, and crack widths were more easily measured compared to the non-pastel base latex paint. The global wallboard behavior was similar to Stage 1 at the same drift with some local variation. Damage was observed at repair locations prior to what was previously observed, but the damage was not significant. The global wallboard damage is shown in Figure 6.53. Typical wallboard cracking occurred at the wall opening corners, and some joint tape tearing was observed at locations where the previously damage joint tape was stripped and replaced. For the innovative repair at the door opening corners, cracking of the finish over the caulking first occurred during the 0.2% [0.36%] drift cycles and not earlier in the loading protocol. The damage was effectively confined within the vertical joint. Figure 6.54 and Figure 6.55 show the typical damage sustained by the wallboard up to this level of loading.

6.8 0.4% Drift

Wall behavior from 0.2% to 0.4% drift is characterized by some softening of the wall stiffness, extension of cracks in length and width, development of new cracks branching off primary cracks, and no deterioration of wall response during trailing cycles. The global response for this level of drift for Stage 2 testing is shown in Figure 6.56. For the 0.4% drift cycles, Walls 11 and 12 had maximum displacements of 0.40 in. and 0.79
in, respectively (identified as [0.79%] in subsequent references and figure captions). The corresponding residual drifts at zero wall force for Walls 11 and 12 were 0.149 in. and 0.154 in. respectively.

The maximum net lateral resistance at 0.4% drift for Walls 11 and 12 is 1,248 lbs/ft and 1,430 lbs/ft respectively, considering both positive and negative displacement cycles. The average force resisted for Walls 11 and 12 at 0.4% drift was near 87% of the average ultimate load of both walls for both the positive and negative displacement cycles.

6.8.1 Portland Cement Plaster Damage

The stucco damage for the 0.4% [0.79%] drift cycles was similar to Stage 1 for both walls and the global stucco cracking patterns are shown in Figure 6.57. The fiberglass tape and new finish coat reduced the stucco crack widths for both walls at the same drift, but the actual basecoat crack may be larger than what can be seen in the finish coat. At the peak displacement, the stucco movement was obvious and can be seen in Figure 6.58. Figure 6.59 shows the magnitude of damage sustained to the stucco at the sill plate level. Figure 6.60 to Figure 6.64 shows the local stucco cracking at the wall opening corners. Bulging, flaking, and spalling of the finish coat occurred at various locations. At the peak displacement cycles of Wall 12, the fiberglass tape ripped along the length of the cracks as the crack opened. The stucco spalled at some locations along the length of the horizontal stucco crack as the stucco section above the sill plate moved relative to the stucco section below the sill plate (see Figure 6.65).

6.8.2 Gypsum Wallboard Damage

The damage to the gypsum wallboard was in the form of wallboard cracking, joint tape tearing, corner bead cracking, and some minor fastener popping. Some rotation of the individual wallboard sections was also observed with the walls held at the peak displacements as shown in Figure 6.66. The paper tape repairs created some slight bulging of the finish at some locations, whereas the fiberglass tape caused the finish to flake off. The damage above the door was confined to the vertical joint and little damage was sustained by the surrounding wallboard. Figure 6.67 to Figure 6.71 shows the local wallboard damage at wall opening corners.
6.9 0.7% Drift

Wall behavior from 0.4% to 0.7% drift is characterized by some softening of the wall stiffness, extension of cracks in length and width, development of new cracks branching off primary cracks. Significant deterioration of wall response during trailing cycles was observed during this level of drift. The global response for this level of drift for Stage 2 testing is shown in Figure 6.72. For the 0.7% drift cycles, Walls 11 and 12 had maximum displacements of 0.70 in. and 1.36 in, respectively (identified as [1.36%] in figure captions). The corresponding residual drifts at zero wall force for Walls 11 and 12 were 0.278 in. and 0.282 in. respectively.

The maximum net lateral resistance at 0.7% drift for Walls 11 and 12 is 1,670 lbs/ft and 1,513 lbs/ft respectively, considering both positive and negative displacement cycles. The average force resisted for Walls 11 and 12 at 0.7% drift was near 98% of the average ultimate load of both walls for both the positive and negative displacement cycles.

6.9.1 Portland Cement Plaster Damage

The stucco began to visually degrade and spall off at some locations, and bulge in compression at other locations. The horizontal stucco crack at the sill plate became very large for Wall 11, and the observed uplift for each wall was large (see Figure 6.74). Figure 6.75 shows the door shear deformation during the 0.7% [1.36%] drift cycles. Bulging of the finish coat occurred at most locations during the secondary cycles, once the cracks opened during the primary peak cycles. At most locations, the fiberglass repair tape had torn along the length of the stucco crack. At other locations, the stucco finish coat spalled off of the fiberglass tape, or the finish coat adhered to the fiberglass tape as the tape de-bonded from the stucco basecoats. Figure 6.76 to Figure 6.79 shows the typical local damage that occurred at the wall opening locations. Figure 6.80 and Figure 6.81 shows the horizontal stucco cracking that occurred at the sill plate. For Wall 11, the crack became very large and extended the full length of the stemwall at this displacement. The stucco finish coat at the sill plate level spalled as the two stucco sections moved relative to one another.

6.9.2 Gypsum Wallboard Damage

The magnitude of damage sustained by Wall 11 did not significantly increase
from 0.4% to 0.7% drift cycles. The crack widths increased, however few crack lengths increased. The damage sustained by Wall 12 was similar to the damage patterns sustained during the 0.4% [0.79%] drift cycles with the extension of wallboard crack lengths and widths. The sustained wallboard damage for both walls in shown in Figure 6.82 to Figure 6.88.

6.10 Ultimate Strength

Wall behavior from 0.7% drift up to ultimate strength is characterized by softening of the wall stiffness, extension of cracks in length and width, development of new cracks, and significant deterioration of behavior during trailing cycles. The ultimate net lateral resistance for Walls 11 and 12 is 1,810 lbs/ft and 1,513 lbs/ft, respectively which was determined using the maximum forces resisted in each wall. The maximum force of Walls 11 and 12 occurred at 0.975 in. and 1.85 in. respectively. The global response for this level of drift for Stage 2 testing is shown in Figure 6.89.

6.11 Failure

6.11.1 Portland Cement Plaster Damage

The stucco damage at larger displacements was significant at the sill plate and the sill uplift was large as shown in Figure 6.95. As the stucco deteriorated and the cracks originating at the wall opening corners became large, the door and window wall openings began to deform in shear as shown in Figure 6.96. This effect was less pronounced at the window wall openings for smaller displacements. The global stucco damage was similar to what was previously observed for Walls 11 and 12 for the smaller displacement cycles and increased in magnitude for the larger displacement cycles. Figure 6.97 to Figure 6.101 shows observed stucco damage for larger displacement cycles.

6.11.2 Gypsum Wallboard Damage

Gypsum wallboard damage for the larger displacement cycles followed earlier described damage patterns with all cracks increasing in length and width. The wallboard buckled and pulled away from the stud framing for Wall 12 and the base of the wallboard was observed to crush on the stemwall as the wallboard panels were restricted from rotation. All wallboard damage for the larger displacement cycles is shown in Figure 6.102 to Figure 6.106.
6.11.3 Measured Response: Stage 2

Global Response

The global wall response of the walls at failure can be seen in Figure 6.90 for Walls 11 and 12 for Stage 2 testing.

Anchorage Uplift Force

Figure 6.91 shows the measured anchor bolt uplift forces at varying levels of drift for the positive and negative displacement cycles measured for Walls 11 and 12. The anchorage force load cells at location 1 was damaged and is not reported for Wall 11 negative displacement cycles thus the anchorage forces shown are for location 4 which measured the largest anchorage uplift forces for positive displacement cycles.

The trend for both walls shows that the anchor bolt forces continually increase up to a drift level of 1.0%, then decrease as the wall displacement increases. This is caused by the different displacement mechanisms of the wall at different levels of drift. At lower drift levels, the walls rock more or less as a rigid body. The results are similar to what was observed in the testing of Walls 5 to 8. See Chapter 4.

Stud Uplift

Stud uplift was another displacement mechanism that was directly measured and represents the displacement between the top of the sill plate and the bottom of the studs. Figure 6.92 shows the stud uplift calculated by subtracting the measured sill plate uplift from the stud uplift since both quantities were referenced from the testing frame. The total uplift at both wall ends was observed to be very close in magnitude and the sill plate uplift varied. Again, the stud uplifts measured increase with increasing displacement, which is expected, and the walls responded similarly as previously noted for all other walls tested.

Wall Pier Rotation

Inclinometers were placed at the mid-height of the wall piers at the wall mid-height to measure any rigid body rotation of the individual stucco wall piers. Chapter 2 discusses the locations of the inclinometers along the length of the walls. When the stucco panels rotated, the force distribution to the nails was more evenly distributed to the furring nails connecting the stucco to the framing. The measured rotations at various locations on the walls are shown in Figure 6.93 and Figure 6.94 and follow nearly the identical trend of increasing with increased displacement for both walls.
Table 6.1 Stucco Repair Methods

<table>
<thead>
<tr>
<th>Location</th>
<th>Method</th>
</tr>
</thead>
</table>
| 1        | California Plastering Consultants Specification  
Grind finish coat  
Rout cracks  
Acrylic bonder  
Fiberglass tape  
Dry Bond  
Finish coat |
| 2        | Provide 2-1/2 in. deck screws @ 12 in. o.c. to sill crack at stemwall |

Table 6.2 Wallboard Repair Methods

<table>
<thead>
<tr>
<th>Location</th>
<th>Method</th>
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<tbody>
<tr>
<td>1</td>
<td>Rout and fill cracks</td>
</tr>
<tr>
<td>2</td>
<td>Rout cracks, cover with fiberglass tape, finish</td>
</tr>
<tr>
<td>3</td>
<td>Rout cracks, cover with paper tape, finish</td>
</tr>
<tr>
<td>4</td>
<td>Strip damaged joint tape, apply fiberglass tape, finish</td>
</tr>
<tr>
<td>5</td>
<td>Strip damaged joint tape, apply paper tape, finish</td>
</tr>
</tbody>
</table>
| 6        | Install vertical joint at opening corner with 1/8" caulked gap, finish  
Reset fastener popping and add extra fastener @ 1 in. away |
Figure 6.1 Global Response of Walls 11 and 12 for 0.2% [0.29%] Drift
Figure 6.2  Stucco Cracking after 0.2% [0.38%] Drift
Figure 6.3  Wall 11 Stucco Cracking after 0.2% Drift
Figure 6.4 Wall 11 Stucco Cracking after 0.2% Drift
Figure 6.5 Wall 12 Stucco Cracking after 0.2% [0.38%] Drift
Figure 6.6 Wall 12 Stucco Cracking at Sill Plate at +0.2% [0.38%] Drift
Figure 6.7  Wall 11 Stucco Cracking at Sill Plate at +0.2% Drift
Figure 6.8  Wall 12 Stucco Cracking at Sill Plate after 0.2% [0.38%] Drift
Figure 6.9  Wallboard Damage after 0.2% [0.38%] Drift
Figure 6.10  Wall 11 Wallboard Damage after 0.2% Drift
Figure 6.11  Wall 11 Wallboard Damage after 0.2% Drift
Figure 6.12 Wall 12 Wallboard Damage after 0.2% [0.38%] Drift
Figure 6.13  Global Response of Walls 11 and 12 for 0.4% [0.78%] Drift
Figure 6.14  Stucco Cracking after 0.4% [0.78%] Drift
Figure 6.15 Wall 12 Stucco Damage at +0.4% [0.78%] Drift

Figure 6.16 Wall 12 Stucco Uplift at –0.4% [0.78%] Drift
Figure 6.17 Wall 11 Stucco Cracking after 0.4% Drift
Figure 6.18  Wall 11 Stucco Cracking Damage after 0.4% Drift
Figure 6.19  Wall 12 Stucco Cracking after 0.4% [0.78%] Drift
Figure 6.20  Wall 11 Stucco Cracking at Sill Plate at +0.4% Drift
Figure 6.21 Wall 12 Stucco Cracking at Sill Plate at +0.4% [0.78%] Drift
Figure 6.22  Wall 11 Stucco Cracking at Sill Plate after 0.4\% Drift
Figure 6.23  Wall 12 Stucco Cracking at Sill Plate after 0.4% [0.78%] Drift
Joint tape tearing

Distributed cracking

(a) Wall 11

Joint tape tearing

(b) Wall 12

Figure 6.24 Wallboard Damage after 0.4% [0.78%] Drift
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Figure 6.38 Fiberglass Tape Application

Figure 6.39 Dry Bond Application
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(b) Finished Repair

Figure 6.47 Fastener Popping Repair
(a) Removed Wallboard  
(b) New Wallboard Installed  
(c) L-molding and Caulk Installation  
(d) Finished Repair  
(e) Finished Repair after Joint Compound and Painting

Figure 6.48 Wallboard Repair above Door
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(a) Stucco Crack at Sill Plate

(b) Stucco Crack Joining at Adjacent Window Openings

(c) Stucco Crack at Sill Plate

(d) Stucco Crack Joining at Adjacent Window Openings

(e) Stucco Crack Joining at Adjacent Window Openings

Figure 6.51 Wall 11 Stucco Cracking after 0.2% Drift

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(a) Stucco Cracking at Window Opening

(b) Repair Finish Bulging

(c) Stucco Damage at Sill Plate

Figure 6.52  Wall 12 Stucco Damage after 0.2% [0.36%] Drift
Figure 6.53  Wallboard Damage after 0.2% [0.36%] Drift
Figure 6.54  Wall 11 Wallboard Damage after 0.2% Drift
Figure 6.55  Wall 12 Wallboard Damage after 0.2% [0.36%] Drift
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Figure 6.58  Stucco Movement at Sill Plate at +0.4% [0.79%]

(a) Stucco Movement  
(b) Stucco Separation

Figure 6.59  Stucco Damage at Sill Plate at +0.4% [0.79%]

(a) Wall 12

(b) Wall 11
Figure 6.60  Wall 11 Stucco Damage after 0.4% Drift
Figure 6.61 Wall 11 Stucco Damage after 0.4% Drift
Figure 6.62 Wall 11 Stucco Cracking at Window Corners after 0.4% Drift
Figure 6.63 Wall 12 Stucco Cracking after 0.4% [0.79%] Drift
Figure 6.64  Wall 12 Stucco Cracking at Sill Plate after 0.4% [0.79%] Drift
Figure 6.65  Wallboard Damage after 0.4% [0.79%] Drift
Figure 6.66  Wall 12 Wallboard Rotation at Repair at +0.4% [0.79%]
Figure 6.67  Wall 11 Wallboard Damage after 0.4% Drift
Figure 6.68  Wall 11 Wallboard Damage after 0.4% Drift
Figure 6.69  Wall 11 Joint Tape Tearing after 0.4% Drift
Figure 6.70  Wall 12 Wallboard Damage after 0.4% [0.79%] Drift
(a) Corner Bead Cracking
(b) Joint Tape Tearing

Figure 6.71  Wall 12 Wallboard Damage after 0.4% [0.79%] Drift
Figure 6.72 Global Response of Walls 11 and 12 for 0.7% [1.36%] Drift for Stage 2
Figure 6.73  Stucco Damage after 0.7% [1.36%] Drift
Figure 6.74  Stucco Cracking at Sill Plate at +0.7% [1.36%] Drift
Figure 6.75  Wall 12 Door Deformation at +0.7% [1.4%] Drift
Figure 6.76  Wall 11 Stucco Cracking after 0.7% Drift
Figure 6.77  Wall 11 Stucco Cracking after 0.7% Drift
Figure 6.78  Wall 11 Stucco Cracking at Windows after 0.7% Drift
Figure 6.79 Wall 12 Stucco Damage after 0.7% [1.36%] Drift
Figure 6.80  Wall 11 Stucco Cracking at Sill Plate after 0.7% Drift
Figure 6.81  Wall 12 Stucco Damage at Sill Plate after 0.7% [1.36%] Drift
Joint tape tearing

Joint cracking

Figure 6.82 Wallboard Damage after 0.7% [1.36%] Drift
Figure 6.83  Wall 12 Wallboard Rotation at +0.7% [1.36%] Drift

Figure 6.84  Wall 11 Wallboard Damage after 0.7% Drift
Figure 6.85  Wall 11 Wallboard Damage after 0.7% Drift
Figure 6.86  Wall 11 Joint Tape Tearing

Figure 6.87  Wall 12 Joint Tape Tearing/Wallboard Cracking after 0.7% [1.36%] Drift
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Figure 6.89 Global Response of Walls 11 and 12 at Ultimate Strength for Stage 2
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Figure 6.91  Anchorage Uplift Forces
Figure 6.92 Stud Uplift of Walls 11 and 12
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Figure 6.95  Stucco Cracking at Sill Plate at +1.0% [2%] Drift
Figure 6.96  Wall 12 Door Deformation at +1.0%  [2%] Drift
Figure 6.97 Stucco Cracking at Sill Plate at +1.5% [3%] Drift
Figure 6.98  Wall 11 Stucco Cracking at Sill Plate at +2.0% Drift
(a) Corner Stud Twisting

(b) Door Deformation

Figure 6.99 Wall 12 Damage at +2.0% [4.0%] Drift
Figure 6.100  Wall 11 Stucco Cracking at Adjacent Window Openings after 2.0% Drift

Figure 6.101  Wall 11 Stucco Cracking at Sill Plate after 2.0% Drift
(a) Wallboard Rotation

(b) Joint Tape Tearing/Wallboard Cracking

Figure 6.102  Wall 12 Wallboard Damage at +1.0%  [2%] Drift
(a) Wall 11

(b) Wall 12

Figure 6.103 Wallboard Damage at +1.5% [3%] Drift
Figure 6.104 Wall 12 Wallboard Damage at 2.0% [4.0%] Drift
Figure 6.105  Wall 11 Wallboard Damage after 2.0% Drift
(a) Stucco Separation at Sill Plate

(b) Wallboard Damage

Figure 6.106  Wall 12 Damage after 2.0% [4.0%] Drift
Chapter 7  Comparison of Results

7.1  Introduction

For both Phase I (Arnold et al, 2002) and Phase II, a total of 12 wall specimens were tested. Selected parameters were varied between the two phases of testing to allow for a comparison of wall behavior for both local and global response in the form of visual damage and measured response. The most significant variable between the two phases of testing was the boundary conditions. Phase I testing had an imposed dead load and boundary conditions at the top of the wall consistent with the first level walls of a two-story structure. A continuous structural steel wide flange section was used to impose the applied lateral force as well as simulating the stiffness of a floor diaphragm and second floor walls above framing into the top of the wall. Phase II testing had an imposed dead load and boundary conditions at the top of the wall consistent with the walls of a single story structure. The continuous wide flange section was replaced with four-twelve inch sections of wide flange beam and a ¼ in. steel strap to transfer the applied load and simulate the less stiff roof diaphragm. Also included in the Phase II testing was the addition of a concrete stem at the base of the wall to simulating a slab-on-grade/stemwall condition presented in Chapter 6 and the absence of ½ in. chop strand fibers for Walls 7 and 8 to see if any effect on strength could be observed.

7.2  Geometry and Boundary Condition Effects

By altering the test specimen boundary conditions, changes in the global and local wall responses could be identified for both visual and measured performance. The single-story versus the two-story boundary condition was observed to affect the measured responses while the visual performance of the walls was similar. The difference in wall specimen geometry was also observed to dictate both global and local wall response with some slight local visual and measured damage differentiation. The same was also observed for the addition of a concrete curb at the base of the testing frame upon which the walls were anchored.

7.2.1  One-Story versus Two-Story

The visual performance of the walls was similar and no significant differences were observed. Figure 7.1 shows the relative observed stucco damage between Walls 1 and 2 versus Walls 5 and 6. The magnitude and pattern of finish damage was similar for
all stages of testing for both the stucco and wallboard materials.

Both the global and local measured response of the walls was affected by the change of boundary conditions, which altered the deformation mechanics. The backbone curve comparison is shown in Figure 7.2. The two-story boundary condition specimens consistently had greater ultimate strengths and larger deflections at ultimate strength than the single-story test specimens. Wall panel rotations, stud uplift, and wall anchor force comparisons are shown in Figure 7.3 to Figure 7.12. The wall panel rotations and stud uplifts are consistently larger for the single-story boundary conditions for nearly all locations with little variation. Figure 7.13 shows virtually no change in the equivalent viscous damping for the varied boundary conditions.

7.2.2 Two Windows versus Door and Window

For both the two-story and single-story wall specimens, the ultimate strengths of the walls were similar when comparing the gross lateral resistance, however due to the difference in the net wall lengths (8’ versus 9’-4”) the walls with two windows exhibited larger net lateral resistances. The strength contribution of the longer central pier for the walls with the door and window was offset by added flexibility of the narrow pier next to the door at the end of the specimen. This tall, slender 2 ft pier contributed much less to the overall performance when compared with the 2 ft piers for the walls with two windows.

Some local changes in the finish damage were observed between the walls with two windows versus the walls with the door and one window. The slender wall pier at the end of the walls with the door and one window was damaged early in the testing whereas the same wall pier located at the end of the wall for the two window test specimens did not deteriorate until larger displacements were imposed. The pulling away of the stucco from the sill plate occurred at smaller displacements for the door / window configuration versus the two window configuration. Virtually no difference in the gypsum wallboard finish damage was observed with the exception of wallboard buckling in the door / window specimens at displacements beyond ultimate strength.

7.2.3 Stemwall Effects

The addition of a concrete stemwall to the base of the walls and extending the stucco continuously past the sill plate and over the concrete stemwall significantly changed the initial wall response. The walls were observed to have a much higher initial
stiffness and achieved higher strengths at the same displacements as the single-story walls without a stemwall. The backbone curves for single story test specimens with and without the concrete stemwall for Stage 1 and failure is shown in Figure 7.14 and Figure 7.15. The initial stiffness for Walls 11 and 12 shown in Figure 7.14 is much higher than for the walls without the stemwall. Walls 11 and 12 were also observed to have a higher ultimate strength than the walls without the stemwall. Figure 7.15 doesn’t show the initial stiffness difference seen in Figure 7.14 due to the sill plate-stucco interface being previously fractured during the Stage 1 testing.

7.3 Fiber Effects

The introduction of the ½ in. chop strand fibers in the stucco scratch coat has virtually no effect on the initial stiffness or ultimate strength when comparing the backbone curves for Walls 5 and 7 and Walls 6 and 8 shown in Figure 4.52. The chop strand fibers also did little to inhibit the cracking of the stucco under load, as both walls with and without the chop strand fibers had similar magnitudes of stucco cracking as shown in Figure 3.1 and Figure 3.5.

7.4 Repair Efficacy

The repairs used for the walls covered in Chapter 6 effectively restored the finish appearance of the walls – the nature and extent of visual were nearly identical for the repeated loading cycles. The high initial stiffness of the walls before the stucco sill plate interface was fractured could not be repaired to a level where the initial stiffness was restored and is shown in Figure 7.16. However, the ultimate strengths of the specimens were actually slightly higher than Walls 5 through 8.
Figure 7.1  Observed Stucco damage for 0.2% Drift
Figure 7.2 One-Story vs. Two-Story Backbone Curve Comparison

(a) Walls 1 and 5

(b) Walls 2 and 6
Figure 7.3  Central Pier Rotation Comparison for Walls 1 and 5 (Location 2)
Figure 7.4  End Pier Rotation Comparison for Walls 1 and 5 (Location 3)
Figure 7.5 North End Pier Rotation Comparison for Walls 2 and 6 (Location 1)
Figure 7.6  Central Pier Rotation Comparison for Walls 2 and 6 (Location 2)
Figure 7.7 South End Pier Rotation Comparison for Walls 2 and 6 (Location 3)
Figure 7.8  Stud Uplift Comparison of Walls 3 and 5
Figure 7.9 Stud Uplift Comparison of Walls 4 and 6 (1 and 2)
Figure 7.10 Stud Uplift Comparison of Walls 4 and 6 (3 and 4)
Figure 7.11  Anchor Force Comparison of Walls 1 and 7

(a) Anchor Location 1 Walls 1 and 7

(b) Anchor Location 2 Walls 1 and 7
Figure 7.12  Anchor Force Comparison of Walls 2 and 8
Figure 7.13 Equivalent Viscous Damping Wall 1 and Wall 5
Figure 7.14 Backbone Curve Comparison for Stemwall Effects
Figure 7.15  Backbone Curve Comparison for Stemwall Effects
Figure 7.16 Backbone Curve Comparison for Stage 1 Repair
8.1 Summary

This report summarizes the results of Phase II of the CUREE wall testing program. Eight 8 ft by 16 ft wall specimens representative of conventional single-story woodframe construction in the 1970s with stucco and drywall finishes and doors and windows were constructed and tested under the CUREE displacement controlled loading protocol (see Chapter 2 for all testing information and construction details).

The first two sets of wall specimens were cyclically loaded to failure. From the global force-deformation curves, drift ranges associated with wall response and damage characteristics were identified as Stage 1, Stage 2, Stage 3, and Stage 4, as described in Chapter 1. Walls 9 and 10 were accidentally destroyed as discussed in Chapter 5. The final set of wall specimens, Walls 11 and 12, included a concrete stemwall with stucco applied continuously across the interface between the wood framing and the concrete. Those walls were tested to 0.4% drift and repaired. Various repair methods were used at this level of drift for both the exterior stucco finish and the interior gypsum wallboard finish. Table 6.1 shows the repair methods used for repairing the stucco at Stage 1 and Table 6.2 shows the wallboard repair methods used at Stage 1. During subsequent testing, the visual performance of each repair method was carefully documented. The visual performance and the structural response were both considered in determining the efficacy of the various repair methods. The varying boundary conditions for the test specimens of Phase I (Arnold et al, SSRP 2002/07) versus Phase II was also investigated for the effects on the visual and measured wall response. The conclusions drawn are as follows.

8.2 Conclusions

8.2.1 Structural Response

(1) Wall test specimens with single-story boundary conditions exhibited ultimate strengths of 11 to 12 kips at 1% to 1.5% drift. This strength is approximately 25% less than the strength of walls tested with two-story boundary conditions in Phase I. While the drift at ultimate strength was consistent with prior studies, the strength per net wall length was greater than shown in prior tests of solid wall panels with stucco, or as permitted by current codes
The high level of strength is attributed to the greater length of effective anchorage relative to the net wall length, and the wrapping of the stucco at the corner studs. The greater wall strength observed in the testing of walls whose configuration more accurately reflects typical construction explains, in part, the relatively good performance of conventional single-family houses during the Northridge Earthquake.

At drift levels below 0.7%, little or no deterioration (either structural or cosmetic) was observed during trailing cycles. Existing stucco cracks caused by one level of displacement did not increase in magnitude when subjected to smaller trailing displacement cycles.

When uncracked, stucco extending across the interface of the mudsill and the concrete foundation increases the initial stiffness of the wall, relative to walls with stucco terminated at the mudsill. Once the stucco cracks at the sill line (typically in the range of 0.2% to 0.4% drift), overall performance of the wall is similar to that of walls with the stucco terminated at the mudsill. The initial uncracked stiffness was not recoverable with the repair methods used in this study.

The structural framing sustained very little damage at all drift levels. The majority of damage was concentrated in the finish materials.

8.2.2 Portland Cement Plaster

Phase I and Phase II testing demonstrated a clear correlation between the pattern of stucco cracking and maximum sustained drift. For walls with openings, the pattern and extent of cracking provide an excellent qualitative indicator of the structural history and health of the wall. In the absence of significant pre-earthquake cracking of the stucco, stucco crack widths provide another possible indicator of maximum sustained drift.

Wall specimens experiencing roughly 0.2% drift had average stucco crack widths of near 0.01 in. and few greater than 0.016 in. Damage is limited to small cracks originating at opening corners.

Wall specimens experiencing roughly 0.4% drift had average stucco residual crack widths of roughly 0.017 in. and few greater than 0.025 in. Some stucco cracks were observed to extend to the stucco boundaries. Primary cracks had new cracks branching off at wall opening corners. Cracks originating at adjacent wall
opening corners exhibited a tendency to join in a near horizontal fashion.

(3) Wall specimens experiencing roughly 0.7% drift had average stucco crack widths near 0.045 in. and few greater than 0.05 in. The stucco cracking patterns extended up to the stucco boundaries and most of the primary cracks originating at wall opening corners have one or more cracks branching from them. Finish coat flaking was also observed at various wall opening locations. Some irregular stucco cracks were also present (i.e. cracks originating at the center of the wall pier).

Stucco repair methodologies were compared at the same drift levels for all locations in order to determine if the repairs were effective in reducing the local magnitude of damage.

(1) Stage 1 Repair (at 0.4% Drift [0.8%]): Grinding off a portion of the finish coat and applying an acrylic bonder and fiberglass tape along the length of the crack was an effective repair method for damage at this drift level. The stucco cracks reopened along the original lengths but did not significantly increase in length or width. Cracking of stucco along the sill line occurs near drift levels associated with the cosmetic damage state and is considered an aesthetic nuisance and not a major structural concern. Some initial stiffness is unrecoverable, however the ultimate strength of the walls was not compromised.

(2) Building paper tearing occurred at drift levels near or greater than the ultimate strength of the walls.

8.2.3 Gypsum Wallboard

From judging the visual damage that occurred to the gypsum wallboard panels, various damage characteristics can be assigned to the wall specimens and related to a probable level of imposed drift.

(1) The gypsum wallboard sustained very little damage at the Stage 1 drift level of 0.2%. Small hairline cracks formed at most wall openings and along the length of the corner bead. All cracking was typically less than 0.002 in. A small number of fastener pops was observed near the wallboard panel boundaries at some locations and some very minor joint tape tearing was observed.

(2) At the Stage 2 drift level of 0.4%, the gypsum wallboard joints began to slightly deteriorate which was apparent by the joint tape beginning to tear along its length.
Corner bead damage increased, and fastener popping occurred near the wallboard panel bottom perimeter, however the cracking was still near 0.002 in.

(3) The interior gypsum wallboard finish sustained significant damage during Stage 3 loading up to a drift of 0.7%. The wallboard cracking ranged from less than 0.007 in. to 0.025 in. Many interior wallboard joints sustained damage or joint tape tearing. Fastener popping is much more obvious, especially at the wallboard perimeter locations. The corner bead at some window opening locations sustained cracking along the full length of the corner bead.

Gypsum wallboard repair methodologies were also compared at the same drift levels for all locations in order to determine if the repairs were effective in reducing the local damage.

(1) Stage 1 Repair: The use of fiberglass tape at wall opening corners was effective in reducing the measured crack widths at most locations, but wallboard finish flaking was prevalent at some locations, making crack width measurements difficult. All wallboard joint damage was essentially repeated at the same drift levels as previously observed. The removal and replacement of various wallboard sections was effective for reducing the crack widths and lengths at those opening locations, but the wallboard damage was then concentrated in the new wallboard joints. The application of fiberglass tape along the length of the corner bead was effective in that no damage was observed at that location until the same level of drift sustained by the previous wall, however the damage was slightly more noticeable in the form of increased finish flaking and cracking. The addition of supplemental screw fasteners was very effective in reducing the amount of observed wall fastener popping, and eliminated the separation of the wallboard from the structural framing. Installation of control joints above the corners of the door opening was effective in confining all damage below the ultimate strength of the walls to the caulked joints and proved to be an easy repair method for controlling the locations of where future cracking will occur.

8.3 Commentary

Because of the relative lack of information on the effects of interior and exterior wall finishes on the global response of a structure, more research needs to be conducted
in order to meet the demands of current construction practice and engineering. Within the past 15 to 20 years, various earthquakes have exposed deficiencies in our understanding of the seismic performance woodframe structures.

The large amounts of damage sustained by some structures led many to believe that the current design procedures were insufficient and that too much shear resistance was allotted to wall finish materials, particularly exterior portland cement plaster and interior gypsum lath and plaster. After inspection, it was common that the design deficiencies, poor workmanship and deterioration of the construction were common flaws that caused structural damage to the building. Rather than more effectively monitor quality control, the buildings codes reduced the amount of shear resistance for which wall finish materials may be assigned. Nowadays, it is not uncommon to completely neglect the shear resistance of wall finish materials in high seismic zones since the allowable design values are so low.

Neglecting the contribution of wall finish materials to the overall shear strength and stiffness of a structure could lead to a structure that behaves much differently than contemplated by the designer. Using the principles of capacity design, neglecting the effects of certain structural elements of a building to the overall performance can lead to undesirable performance. The actual force demand on certain structural components of a shear wall stiffened by finish materials may actually be significantly higher than the calculated demand during a seismic event due to the larger attraction of force. If the seismic demand is too large and the designed structural components cannot meet the actual demand, an undesirable failure mode could occur, which is contrary to structural engineering philosophy. Buildings may also be significantly over designed per the current codes, which is also contrary to the practice of structural engineering that is largely based on economic use of materials.

8.4 Recommendations for Future Studies

Based on the finding presented herein, recommendations for further studies should include:

1. Variation of the relative size and location of wall openings and pier widths.
2. Variation of stucco attachment with and without structural sheathing.
3. Variations of weep screeds and stucco attachment at the sill plate level.
4. Variations of dead load and boundary conditions.
5. Variations of mechanical holdowns and locations.
6. Data interpretation would be facilitated by use of leading and trailing cycles of the same amplitude, rather than the 75% trailing cycles used in this study.
7. Further variation of wall boundary conditions commonly found in woodframe construction.
8. Testing of walls constructed consistent with current engineering practice and the 1997 UBC and equivalent codes in current practice.


