CYCLIC BEHAVIOR AND REPAIR OF STUCCO AND GYPSUM WOODFRAME WALLS: PHASE I

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CUREE, the Consortium of Universities for Research in Earthquake Engineering, is a non-profit organization incorporated in 1988 whose purpose is the advancement of earthquake engineering research, education, and implementation. There are 28 University Members of CUREE located in 18 states and approximately 340 individual professor members.

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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.
Cyclic Behavior and Repair of Stucco and Gypsum Sheathed Woodframe Walls: Phase I

by

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Final Report on a Research Project Funded by the Consortium of Universities for Research in Earthquake Engineering

May 2003

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Abstract

In an effort to gain a better understanding of the cyclic behavior of woodframe structures, the Consortium of Universities for Research in Earthquake Engineering (CUREE), with funding from the California Earthquake Authority (CEA), sponsored a woodframe wall testing project at the University of California, San Diego. The project was conducted in two phases. Phase I (presented herein) investigated the response of woodframe walls having boundary conditions consistent with the first level walls of a two-story structure, and Phase II (Arnold et al, SSRP 2003/02) 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 in California. A typical 7/8 in. three-coat Portland cement plaster system (stucco) applied to open framing (i.e., no structural sheathing nor diagonal bracing) was used for the exterior wall finish and 1/2 in. gypsum wallboard (drywall) was used as the interior wall finish. Two separate wall configurations with openings were tested under reversed pseudo-static cyclic loading conditions. The data obtained from the testing of the first pair of test specimens was used to determine 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.

The second pair of wall specimens were tested up to each drift level, repaired, and retested to that drift level to determine the efficacy of various stucco and drywall repair methods. From the relationship between crack patterns, residual stucco crack width, residual story drift, and maximum story drift, an estimate of the structural damage to walls of similar construction can be classified according to the damage state. The repair methods used at each damage state were monitored to determine the aesthetic and structural performance of each repair method. Local variation of damage occurred and was dependent on the repair method, but the global crack patterns were similar. The repair methods were effective in restoring the strength of the original wall specimens for walls that had been loaded up to 90% of specimen capacity.
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Funding for the research detailed in this report was provided by the Consortium of Universities for Research in Earthquake Engineering (CUREE), under a contract with the California Earthquake Authority (CEA). Acknowledgement is gratefully given to the Stucco Manufacturers Association for their material donations, Sorrento Plastering for providing all plastering services, and Andrew Gillespie and Associates for conducting all wall repairs. Michael Roberts of the California Plastering Consultants is also acknowledged for the generous donation of money towards the fabrication of the test specimens. The specimens were built and tested at the Powel Structural Systems Laboratories at the University of California, San Diego. Without the assistance and guidance of the technical staff, specifically Alex Sherman and Charlie Stearns and the help of the undergraduate students, the project would not have been such a success.
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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, as well as relating corresponding visual documentation to various levels of structural damage.

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 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 (stucco) 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.\(^1\) 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 to 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, two layers of Grade D type building paper have 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. This shrinkage will typically create randomly distributed cracks in solid stucco panels. Where openings are present, the cracks will tend to emanate from the corners of openings in the

\(^1\) The one-coat system, primarily used in hotter climates, was innovated 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.
Another common cause of non-structural cracking is due to diurnal thermal cycling of the stucco. 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 and 4 ft by 12 ft. The basic gypsum wallboard system is composed of the gypsum wallboard panels attached to the structural framing members using mechanical fasteners, often phosphate covered cooler nails or, more recently, screws. At locations where individual wallboard panels meet, joint compound, along with either paper or fiberglass joint tape, 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 CUREE/CEA 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 (CEA), a testing program to assess earthquake damage in residential woodframe wall construction 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, strength, stiffness, 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
3. determination of the visual and structural performance of various finish repair methodologies.

The project was conducted in two phases. Phase I involved the simulation of the first story walls of a two-story structure, and is covered in this report. Phase II is reported in Arnold et al. (2003). 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 (i.e., no deterioration of stiffness or loss of strength. 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, but no loss of strength. 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 damages is defined as the damage state associated with some softening or loss of stiffness, but no loss of ultimate strength. 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 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 window corners, 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 four 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.

Various literature available on the cyclic performance of gypsum wallboard and stucco was reviewed and is summarized in Chapter 2. The test setup, specimen construction and specifications, loading history, and instrumentation are covered in Chapter 3. In Chapter 4, the test results of the first 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 data gathered during the testing of the first pair of specimens, various levels of drift were associated with the prescribed qualitative damage state definitions.

The test results of the second pair of test specimens are presented Chapter 5, which covers the four stages of testing. For each stage of testing, the repair methods used are compared for relative performance, both aesthetically and structurally. The performance of the repairs is evaluated in Chapter 6. Chapter 7 presents the correlation of various measured data and the development and application of a procedure for evaluating the structural damage of a wall using the measured residual crack widths and
the residual drift. Chapter 8 covers the conclusions drawn from the project and the recommendation of future studies on various woodframe construction issues.
Figure 1.1  Open Stud Construction
Chapter 2  Literature Review

2.1 Introduction

Seven publications were reviewed to examine the effects of finish materials on wall strength, ductility, and visual damage states. The following sections provide brief descriptions of the research performed and the conclusions drawn.

2.2 Wolfe (1983)

Wolfe investigated the contribution of gypsum wallboard to the racking resistance of gypsum-sheathed walls. The study focused on the ability of gypsum-sheathed walls to effectively transmit lateral forces to the foundation, acting as a shear diaphragm. Although the gypsum plaster core is brittle in nature, the paper backing provides strength and stiffness to resist racking forces. This added stiffness of drywall partitions is often neglected when designing the lateral-force-resisting system of a structure. The main objective of the study was to determine the significance of gypsum wallboard contribution to wall racking resistance, as well as evaluating the influence of wallboard/frame interaction, panel orientation, and wall length to the shear wall capacity.

Overall, thirty walls consisting of thirteen different wall configurations were tested. Test variables included varying wall lengths, and panel orientation. All gypsum wallboard was 1/2 in. and no other sheathing material was used. All structural framing was construction-grade spruce-pine-fir, and all studs were 2 in. by 4 in. spaced at 24 in. on center. The walls had a single top plate, a single bottom plate, and single corner studs at wall ends. The top and bottom plates were attached to the studs by face nailing 2-16d common nails per stud. The control wall consists of an 8 ft by 8 ft wood frame and a wallboard diaphragm. Two 4 ft by 8 ft wallboard panels were applied parallel to the wall height dimension. Three wall lengths were used for this study, 8 ft, 16 ft and 24 ft. The different wallboard configurations considered consisted of fastening the larger wallboard length either in the horizontal or vertical direction. Twenty-two of the thirty walls had 1/2 in. gypsum wallboard attached to one side only, the remaining eight walls had diagonal bracing, but no wallboard sheathing.
Taped-wallboard joints, cyclic load-displacement characteristics, and wall failure mechanism were all shown to be independent of the wall configuration or construction detail. None of the walls showed any weakness along the wallboard joints, which indicates that the taped joint transfers the load very well and allows the wall panels to act as a rigid body. The one failure mechanism consistent with all wall configurations was the nails bending and tearing through the paper surface. This most commonly occurred around the wall perimeter. The gypsum walls primarily had fastener failure along the top and bottom plates, originating at the tension corner and reducing in severity toward the mid-height of the wallboard panel.

Along with an overall strength increase due to the longer walls, which is expected, the most obvious change in wall behavior comes from a visible shift in the failure pattern. The wallboard panels showed less tendency to rotate relative to framing and the main failures occurred to the connections along the bottom plate. The wallboard diaphragm displaced in a uniform fashion at the bottom plate, suggesting an equal distribution of stress as well. This explains the sudden failure of the wallboard connections. The 16 ft long walls had nail failures extending nearly to the wall mid-height, whereas the 24 ft long walls had nail failures only 2 ft from the bottom plate.

The effects of gypsum wallboard panel orientation showed a 50% increase in the strength for 24 ft long walls for the horizontal installation versus the vertical installation. For the horizontal installation, a cut edge did not exist along the bottom and top edges of the wallboard panel. These edges were confined by the gypsum paper and create more resistance in compression when compared to a cut edge where the gypsum core crumbled, allowing the nails to easily tear through the paper at much lower loads. However, the failure pattern remained the same when compared to similar wall configurations.

It was concluded that wallboard orientation had a significant effect on the overall performance of gypsum-sheathed walls. Walls with 12 ft long horizontally applied gypsum wallboard panels showed as much as a 50% increase in strength when compared to walls which had 8 ft gypsum wallboard panels applied vertically.
2.3 Yasumura and Sugiyama (1984)

Common design practice in Japan regarding shear distribution to woodframe walls consisted of applying 2/3 of the lateral force demand to solid wall segments, and 1/3 to the remaining wall, i.e., intersecting walls, the areas above and below wall openings, etc. The inherent problem with this simplified design process is that at times the shear strength of the walls is over or under-estimated. In order to shed some insight on the matter, Yasumura and Sugiyama initiated a study to investigate the influence of wall panel openings and sheathing orientation on wall strength.

All wall specimens were 1/3-scaled dimensions compared to standard North American construction specifications. All structural framing was 13 mm by 30 mm air-dried western hemlock spaced at 15 cm on center, except for 26 mm by 30 mm members arranged along the vertical joints of plywood sheathing. A double top plate and a single bottom plate were used with end nailing using N32 1.85 mm by 32 mm wire nails. Structural sheathing was 3 mm plywood attached with N19 1.5 mm by 19 mm wire nails spaced 3.3 mm edge nailing and 6.7 mm field nailing. All wall specimens were grouped into one of two groups based on sheathing panel orientation, with Group I walls having the plywood sheathing applied in a single sheet, and Group II having the plywood applied vertically and horizontally in some cases. Within each main group, other subdivisions were made based on opening areas. The test specimen grouping and configurations can be seen in Figure 2.1.

For the Group I wall configurations with windows, the plywood buckled at openings and shortly afterwards, failed in tension at the opposite corners. This pattern was repeated for the wall configurations with door openings. The no opening configurations of Group II had large nail deformations and eventually punched through the sheathing. The Group II wall configurations with relatively large openings exhibited large nail deformations as well as sheathing buckling at opening corners. For the Group I walls with vertical openings between top and bottom plates, the panels on either side tended to deform and rotate equally, with the displacement at mid-height being roughly half the displacement at the top. Group II wall configurations with the vertical plywood sheathing application tended to have the plywood panels displace and rotate independently of one another. Specimens with separately sheathed portions of wall
directly above and/or below the openings showed less bending in the side walls than the singly sheathed walls, which was evident when observing the large joint slippage in between the separate plywood panels. This panel rotation seems to eliminate the tension failures noticed at the opening corners from the wall specimens with singly sheathed walls.

The rotation and shear strain of each plywood sheet in Group II specimens was measured to investigate the shear force distribution in the plywood panel. The more a plywood panel rotates, the less shear strain is imposed on the plywood panel and the more force that is imposed on the nails.

Wall panels with several plywood sheets applied (Group II) eliminates the buckling and tension failures observed around wall openings where an opening was cut out of a single sheet of plywood. The input energy was dissipated through panel rotations and nail deformations rather than the observed buckling and tension failures. When plywood sheathing was applied vertically along the length of a wall, the majority of the shear force was concentrated toward the central panels and less force was attracted to the end panels. This is evident when examining the individual panel rotation, with the exterior panels rotating more than the interior panels. For the walls with three rows of horizontally applied sheets, the plywood panels at the top and bottom of the walls resist the majority of the shear force, while the interior row resisted the least amount of force. The shear stiffness ratio and shear strength ratio increase similarly according to the increase of the opening coefficient regardless of the shape of opening and the method of application of sheathing. The shear stiffness and strength of a wall panel with various openings can be estimated using the prescribed procedure as long as a panel without openings and of the same geometry and materials is known.

2.4 Patton-Mallory et al. (1985)

When designing a proper lateral-force-resisting system for a woodframe structure, the design engineer will simply look up allowable values for the sheathing material that will be used on the project and design the walls accordingly. These design values used for shear resistance were developed using one of two approved methods, ASTM E 72 (ASTM, 1995) or ASTM E 564 (ASTM, 1995), with ASTM E 72 being used more commonly. Prompted by the fact that these testing methods require that the wall
specimen aspect ratio (length/width) be equal to 1, a study proposing the effects of varying the aspect ratio as well as introducing wall openings to wall specimens was carried out by the authors. ASTM E 72 compares the performance of sheathing types and configurations to a standard or minimum performance, while ASTM E 564 allows the changing of wall boundary conditions to represent actual conditions relevant to typical wall performance.

A total of eleven full-scale walls were constructed using 2 in. by 4 in. Spruce-Pine-Fir (SPF) for all structural framing and 1/2 in. gypsum wallboard attached with 1-1/4 in. wallboard nails. One set of walls had gypsum wallboard attached vertically, with the remaining walls having the wallboard attached horizontally. Four of the six walls with an aspect ratio of 3 had double-hung windows, casement windows, and prehung doors installed.

The full-scale testing method was similar to that of ASTM E 564 in that the wall boundary conditions were set up so that actual behavior of woodframe wall in a structure could be represented (It is unclear if any dead load was applied, however previous tests conducted by Wolfe had used dead load and the setup for the full-scale tests appeared to be the same.)

Wall ultimate loads versus aspect ratios were compared for both scaled and full-scale walls. The ultimate load and aspect ratio can be reasonably shown to be a linear relationship for aspect ratios ranging from 1 to 3. The stiffness for the full-scale walls was also checked at 0.05 in. displacement and compared with the aspect ratios, and the relationship was shown to be nonlinear, and appeared to be quadratic. The longer walls were stiffer per unit length versus the shorter walls. The scaled walls showed similar results, yielding a proportional strength to aspect ratio relationship between aspect ratios of 1 to 4.

Two different wall heights were tested. Standard 8 ft plate height walls and smaller 2 ft plate height walls were tested. The full-scale walls had an aspect ratio ranging from 1 to 3, while the scaled walls had an aspect ratio ranging from 1 to 4. Small walls were constructed with 2 in. by 4 in. Douglas Fir (DF) for all structural framing, 1/2 in. gypsum wallboard sheathing, and 1/2 in., 4-ply, CDX plywood sheathing. No grade or stud spacing was specified. The gypsum sheathing was attached using 1-1/4 in.
wallboard screws spaced at 5-7/8 in. horizontally and 5-1/4 in. vertically. The plywood sheathing was attached using 8d common nails spaced at 5-1/2 in. horizontally and 5-1/4 in. vertically. Five different configurations of small walls were tested, single- and double-sheathed plywood walls; single- and double-sheathed gypsum walls, and walls having plywood sheathing on one side and gypsum sheathing on the opposite side. Ten replications of each wall configuration was tested for a total of 200 wall tests.

For the full-scale walls with openings, a predicted response was determined using an effective length factor and scaling down the response of the fully sheathed wall tests. The results matched very well, but the predicted response appeared to overestimate the initial stiffness and underestimate the wall displacements below 0.2 in. The full scale tests yielded ultimate racking loads of 140 lbs/ft, whereas the value determined from ASTM E 72 is 100 lbs/ft, suggesting that the methods used in the study, which simulate ASTM E 564, underestimate the capacity of walls constructed solely with gypsum wallboard.

Similar failure modes were also qualitatively observed for both full-scale and scaled walls sheathed with gypsum as the aspect ratios changed. Smaller aspect ratio walls exhibited more racking behavior, which led to a more evenly distributed fastener damage pattern, whereas the higher aspect ratio walls did not rack as much and the damage pattern was concentrated at the top and bottom plates. This suggests that the racking ability of a wall can affect the wall strength since racking more evenly distributes the lateral load to the nails. The test results also show that wall sheathing strengths are additive.

Another concern regards the allowable shear values assigned to gypsum wallboard. At the 100 lbs/ft level, the gypsum wallboard has sustained considerable damage and may be beyond repair. To control cosmetic damage, the report recommends an allowable drift limit on walls sheathed with gypsum wallboard close to 0.2 in. This is the level at which the wallboard begins to visibly deteriorate although the stiffness does not seem to be seriously degrading.

The ultimate racking strength of gypsum wallboard sheathed walls can be reasonably assumed to be linearly proportional for aspect ratios between 1 and 3. However, the initial racking stiffness is not linearly proportional. The ultimate racking
strength of plywood-sheathed walls were reasonably assumed to be linearly proportional for aspect ratios between 1 and 4. The effective length method of estimating the ultimate strength of gypsum-sheathed walls can accurately predict the ultimate capacity, but the initial stiffness is overestimated using this method.

2.5 Oliva (1985)

Research conducted by Oliva investigated the racking behavior of woodframe gypsum panels under static and dynamic loading. Testing program had a number of objectives including the preparation of a preliminary guide to the deformability of gypsum sheathed walls subjected to monotonic and cyclic loading and to define tolerable levels of deformation without forming visual damage or needing expensive repairs.

A total of twelve walls were tested, six walls used 4d (1-1/4 in.) drywall nails and six walls used 4d nails and a strip of multi-purpose construction adhesive under each nail line. All nailing was spaced at 8 in. on center. Each set of walls, unglued and glued, were subjected to monotonic static testing to one-inch displacement, static cyclic loading, and dynamic loading. Two walls from each set were tested under each mentioned method. Each test specimen had an 8 ft plate height and was 8 ft length. The framing lumber was 2 in. by 4 in. Douglas Fir standard grade. Studs were placed at 23-5/8 in. on center and had 1/2 in. gypsum wallboard placed on one side of each panel. Each specimen had single end studs, a double top plate, and a single sill plate, connected by 2-16d nails at each stud/plate joint. The wall specimens were tested in the vertical position having an imposed gravity load of 450 lbs/ft. The sill plate was attached to a rigid steel foundation member secured with two anchor bolts placed within 12 in. of each panel end. No other restraints at specimen boundaries were used.

The unglued panels tested under monotonic loading conditions displayed constantly varying stiffness, which was defined into a tri-linear load deformation relation broken into “initial,” “yield,” and “plastic” ranges. At the initial proportional limit, the walls provided roughly 100 lbs/ft resistance. At the second proportional limit, 190 lbs/ft of resistance was noted, and at maximum wall displacement (1.0 in.) 245 lbs/ft was achieved. It was shown that softening of the wall was apparent at top plate displacement of 0.1 in. However, visual damage in the form of cracking and spalling of the joint compound over the fastener heads was noticed near the top of the wall at displacements
of the order of 0.3 in. to 0.4 in. At larger displacements, nail heads began pulling through the paper surface. Above displacements of 0.6 in., the gypsum panels pulled away from the framing members, which corresponded to very low stiffness above this displacement level.

The report concludes that deformation of gypsum walls should be limited to 0.2% of the story height if visual damage is to be avoided for unglued walls. Design scenarios should consider whether to prevent any gypsum sheathed panels from reaching these drift limits if the panels are part of the lateral-force-resisting system of a structure. Isolation from the lateral-force-resisting systems may also need to be considered so that this level of damage is avoided. A nailed gypsum wallboard panel can sufficiently resist 100 lbs/ft and still remain essentially linear elastic with a maximum lateral load carrying capacity of 170 lbs/ft.

2.6 Gatto and Uang (2001)

Depending on the desired sheathing material used, the International Building Code (ICC, 2000) provides the practicing engineer with allowable values with which to design woodframe structures. Wall finish materials may be used to aid in the lateral force resistance but only a limited amount, and it is prohibited in Seismic Design Categories E and F. Previous testing has implied that superposition of wall finish materials to the allowable values of a dissimilar material is valid, however this practice is disallowed for seismic design. Gatto and Uang investigated the effects of a realistic dynamic loading on wood-frame walls in order to better understand the effects of wall finish materials and the combined effects on the lateral resistance of the wall systems. Of particular interest was the influence of finish materials on performance parameters related to design such as strength, stiffness, deformation capacity, etc.

A total of eighteen 2.4 m square specimens were constructed using seven different sheathing configurations. All structural framing was 51 mm x 102 mm Douglas Fir Structural No. 2 studs spaced at 406 mm on center. Boundary members were double top plate, pressure treated sill plate, and double end studs. All structural sheathing was 1.2 m by 2.4 m and either 10 mm Oriented Strand Board (OSB) or 12 mm plywood Structural 1 (PWD) sheathing attached to the framing with 8d box nails applied at 102 mm on center at panel perimeter and 305 mm on panel interior. All exterior cladding was 22 mm,
three-coat, Portland cement stucco, and all interior finish was 13 mm gypsum wallboard (GWB) fastened to the wood framing using 32 mm long wallboard screws spaced at 406 mm on center. Paper tape and joint compound was used to properly render the wallboard joint unseen. The wall end studs were attached to the testing frame with commercial holdowns (Simpson Strong Tie HTT22) and two 5/8 in. diameter anchor bolts were also applied per 1997 Uniform Building Code (UBC) standards. All pertinent nailing also followed 1997 UBC standards.

When comparing the walls without finish materials to the identically constructed walls with finish materials, it is obvious that the wall performance is significantly changed at the structural and performance levels. The differences can most notably be observed in the damage patterns and the global wall response. The initial wall stiffness for all specimens was calculated and compared using both ASTM E 564 and FEMA 273 (1997) methods. The ASTM method takes the measure at 33% of the ultimate strength and FEMA uses 80% of the ultimate strength. From the results it is shown that both strength and stiffness are increased due to the addition of wall finish materials. However, due to the increase in strength, a more brittle failure is observed and the deformation capacity is reduced, as the failure patterns shift from the sheathing connections to the structural framing members. It can also be seen that the dynamic effects are not nearly as pronounced as the addition of finish materials.

The general failure modes of wall panels without finish were dominated by nail failure. Nails pulling through the sheathing, nails pulling out of the structural framing, and even nail fracture were all observed. The nail failure allowed for increased panel rotations, which eventually led to wall failure. For the specimens having sheathing on one side only, at failure the corner studs often twisted significantly due to eccentric effects creating torsion in the walls.

Once the finish materials were added, the stud twisting was greatly reduced. The addition of stucco also bonded the individual structural sheathing members, causing them to act as a monolithic unit. The decrease in sheathing rotation more evenly distributed the lateral load, which increased the demand on the studs and the sill plate. This is evident as the primary failure modes changed. Nail failure was less prevalent and studs often broke and the sill plate split in many cases.
Backbone curves were developed from the global hysteresis for the various configurations and compared to one another. The results of which can be seen in Figure 2.2. The GWB only wall was showing a lateral resistance capacity of 2.1 kN/m. When compared to the OSB and the OSB+GWB specimens, it can be reasonably assumed that the contribution of wall finishes to overall strength is additive.

From the test results it is obvious that the addition of wall finish materials significantly affect the wall response and change the shearwall mechanics as well. The finish materials increase strength and stiffness, however deformation capacity is reduced. The addition of GWB seems consequential since a 12% increase in strength is accompanied by a 31% reduction in deformation capacity. A 34% increase in strength accompanies the use of stucco using the prescribed attachment and only a 31% reduction in deformation capacity is noticed. For stucco, the strength gain outweighs the deformation capacity reduction and should be considered in design.

2.7 McMullin and Merrick (2001)

Prompted by the massive damage incurred to interior finish materials during the 1994 Northridge Earthquake, McMullin and Merrick investigated the seismic behavior of gypsum-sheathed walls of various configurations. The overall project goals included defining and quantifying seismic performance levels for gypsum wallboard, establishing engineering parameters and damage threshold deformations of wall systems, and exploring various innovations to wall finishes that will improve overall seismic performance.

Seventeen wall specimens were constructed of varying configurations. All walls had one 2 ft 10 in. wide by 6 ft 10-1/2 in. tall rough opening in the same location for all walls. Wall variables included fastener type and spacing, edge fastening, top plate restraint, addition of a 3 ft by 4 ft rough window opening, wallboard panel orientation, various repair methodologies, innovative construction techniques, and the addition of a door frame, door trim and baseboard. All structural framing was 2 in. by 4 in. Hem-Fir No. 2 or better spaced at 16 in. on center. All walls had a double top plate, single bottom plate, 4 in. by 4 in. corner posts, trimmer and king studs at all wall openings, and 4 in. by 12 in. headers. In order to attempt to simulate ceiling and corner returns, additional wooden members were added to accommodate this condition. All walls were sheathed
with 1/2 in. gypsum wallboard panels applied on both sides of the wall. The 4 ft by 8 ft panels were attached using varying fasteners and fastener spacing scenarios. The gypsum wallboard was installed with the long dimension oriented horizontally, and varying the location of butt joints with respect to wall openings. The wallboard joints were properly hidden using paper tape and joint compound. The only exception of gypsum wall use was for two walls, which had FIBERROCK Brand Panels installed. FIBERROCK is a heavier, abuse resistant alternative to conventional gypsum wallboard.

Various damage thresholds were observed during the testing. Hairline cracks initiating at the opening corners was the most prevalent form of initial damage. Cracking of the finish over the fastener head, cracking of wallboard joints, and the crushing of wallboard at wall boundaries all occurred at larger sustained drifts. Global buckling of large portions of the panels, and the loss of portions or even whole panel sections was noted at large displacement levels.

Two distinct failure modes were observed during the testing. The first failure mode involved the fasteners pulling out of the wallboard along the wall perimeter allowing displacement of the wallboard relative to the framing. It appeared that the upper half of the framing remained essentially vertical, and all the lateral movement occurred by bending of the studs in the lower half of the wall. For this mode, all wallboard joints remained in good condition and free of cracking. The second failure mode observed consisted of wallboard joint failure, allowing relative rotation of individual wallboard panels. This response is more consistent with general wall racking behavior which distributes the wall forces more evenly to the fasteners, incurring much less fastener pull through as a result of less force demand.

Cracking at wall panel openings commonly occurred at drifts of close to 0.25%, with the cracks widening and lengthening at larger displacement levels. Wall fastener popping was also noticed at wall drift levels of 0.25%-0.75%, usually initiating at wall boundaries, particularly at the bottom plate. Maximum wall strength was achieved around 1% drift on average.

All walls, independent of fastener type and spacing, had comparable initial stiffnesses, however the walls having tighter fastener spacing were observed to have less deformation capacity once the peak strength was developed. Perhaps the single most
important parameter having an effect on the ultimate wall strength was the vertical flexibility in the middle of the wall. The walls in which no anchors were installed to resist the vertical movement of the middle portions of the wall pier exhibited lower ultimate strengths than the restrained cases. The restrained walls developed 310 lbs/ft resistance for gypsum wallboard with screws at 16 in. on center while the identical walls allowing vertical movement at the middle portion of the wall pier developed only 194 lbs/ft lateral resistance.

The addition of a window opening did reduce the ultimate strength of the wall. A common assumption that the ultimate strength of the walls is a linear function of the individual wall pier segments is shown to be somewhat inaccurate but not unreasonable. Other interesting findings showed that the floating edge construction technique did not really influence the strength, stiffness, or damage patterns of the comparable walls. The innovative systems implemented for some of the tests showed that they indeed reduce crack lengths and widths at equivalent drift levels for the identical walls.

McMullin and Merrick concluded that both screws and nails achieve acceptable performance levels for gypsum-sheathed walls. The increased density of wall screws significantly influenced wall strength, however resulted in less deformation capacity after ultimate load results. Monotonic loading reasonably predicts the cyclic behavior of gypsum-sheathed walls and damage states are also comparable, although the monotonic loading seems to place an upper bound on attainable ultimate drift. The ability of the wall to move vertically in the middle did show significant influence on both the strength of the wall and the damage developed. The ability of the pier to “roll” as opposed to “rack” appeared to have more effect on the behavior of the walls than any other parameter studied, except the addition of more wall openings.

Improvement in the performance of the wallboard was obtained by making alterations to the installation. Using wallboard of tougher material, fasteners with larger heads, and reinforcing the re-entrant corners of openings all appeared to improve the performance of the walls. Minimal repair methods tested for this project resulted in walls that resisted between 0.803 to 1.235 times the load of the walls before the original damage.
2.8 Fischer et al. (2000)

Fischer et al. investigated the seismic response of a full-scale two-story house subjected to both static cyclic and earthquake dynamic loading. The primary objective of the study was to better understand the seismic behavior of woodframe structural systems as well as determine the effect of both interior and exterior wall finishes on overall seismic performance, since wall finishes are typically ignored when designing for lateral resistance.

The test structure was intended to represent the current practice at the time of design, while fitting within the space constraints of the testing facility. A full-scale two-story home was engineered and built for this purpose. All engineering was performed under the 1994 UBC Zone 4 requirements. The overall floor plan had dimensions of 4.9 m by 6.1 m with 2.4 m story plate heights. A garage door, pedestrian door, and windows were all incorporated into the design. All structural framing was 51 mm by 102 mm Douglas Fir Structural No. 2 studs spaced at 406 mm on center. All structural sheathing was 9.5 mm thick Oriented Strand Board (OSB) fastened with 8d box gun nails. All interior finish was 12 mm gypsum wallboard panels attached with 32 mm long wallboard screws spaced at 400 mm on center for vertical studs and 300 mm on center for all ceiling joists. The exterior finish was a 22 mm thick, 3-coat, Portland cement plaster attached to the wood framing by galvanized 17-gage steel wire lath fastened to the OSB sheathing and vertical studs by 20 mm staples.

The house was tested using a variety of input ground motions selected to represent various levels of seismic hazard. Both an ordinary ground motion and a near-fault ground motion were selected. The ordinary ground motion selected was the 1994 Northridge Earthquake ground motion recorded at Canoga Park. This record was scaled accordingly to represent varying levels of probabilities of exceedance. A 10% probability of exceedance in 50 years or a return period of 475 years (10%/50), a 20%/50, 50%/50, and 99%/50 were all selected as the desired return periods for the Canoga Park ground motion. The near-fault ground motion selected was the 1994 Northridge Earthquake ground motion recorded at Rinaldi Recording Station. This unscaled ground motion represents a probability of exceedance of 2% in 50 years (2%/50) or a return
period of 2475 years. The house was then tested with and without wall finish materials for each of the prescribed ground motions.

Testing showed that the addition of wall finish materials significantly affects the seismic performance of the test specimen. The initial fundamental period of the bare wood-frame structure was 0.25 sec. The fundamental period of the structure after the wall finish was added was 0.15 sec. This is a significant decrease in the fundamental period, which corresponds to a much stiffer structure. The measured increase in lateral stiffness was on the order of 3 times as high as the bare wood-frame structure, when modeled as a single-degree-of-freedom system. When comparing the 1994 UBC empirical equation for fundamental period calculation, it is shown that the UBC equation reasonably predicts the period for a structure including the finish materials.

The observed damage to the bare wood-frame structure included shear wall nail pullout and diagonal cracking of the OSB at various wall opening corners. With the finish materials installed, the same cracking patterns were observed in the stucco and gypsum wallboard. All damage was considered minor for the finish materials.

The addition of the finish materials made a significant contribution to the overall stiffness and strength of the structure. The behavior of the structure incorporating wall finishes is nearly elastic due to the significant increase in lateral stiffness. The pinched nature of the hysteretic response of the bare wood-frame structure indicates that some stiffness and strength degradation is occurring, however this was not observed for the structure with wall finishes. Also, the anchor bolt and holdown tensile forces were more evenly distributed as a result of the wall finishes aiding in the walls acting more as a single unit rather than individual wall segments.

Wall finish materials are not commonly used in the design of a lateral-force-resisting system for wood-frame structures. The results have shown that this may lead to an inaccurate design, since the installation of stucco and gypsum wallboard significantly increase the lateral force resistance of the structure as a whole. An decrease in fundamental period and a redistribution of anchorage uplift was also observed, which furthers the importance of the recognition of finish materials being utilized to resist the seismic demand. It can also be concluded that the 1994 UBC (ICBO, 1994) empirical equation for fundamental period estimation is valid for woodframe structures with stucco
finish. Further research should be initiated to evaluate the seismic resistance of wall finish materials to supplement current design standards.
Figure 2.1 Wall Specimen Configurations

Figure 2.2 Backbone Curve Comparison for (a) East Wall and (b) West Wall (Gatto and Uang 2001)
Chapter 3  Testing Program

3.1  Introduction

Four test specimens were constructed and tested for Phase 1. All were tested under cyclically reversed static loading using the CUREE loading protocol for the testing of woodframe structures (Krawinkler, 2001). Walls 1 and 2 were cyclically loaded to failure. For testing purposes, failure was defined as the point at which the applied load drops for the first time below 80% of the maximum load developed. Walls 3 and 4 were displaced up to target drift levels determined using the data gathered from the testing of Walls 1 and 2. Crack width, extent of visual damage, structural response, and engineering judgment were used to quantify a level of drift associated with each qualitative damage state definition described in Section 1.4.1; the determination of the target drift level for each stage of testing is discussed in Chapter 5. Walls 3 and 4 were loaded up to each target drift level and repaired. After each repair, the walls were reloaded to the same target drift level (starting from the beginning of the loading protocol) and the effectiveness of the repair evaluated. Loading was then continued to the next higher target drift level. This process of load and repair was repeated for each target drift level. The method of loading described is defined as “4-stage” testing. The test matrix is shown in Table 3.1.

3.2  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. Figure 3.1 shows various test frame components and Figure 3.2 gives some general frame dimensions. Figure 3.3 and Figure 3.4 show the testing frame with the actuator and test specimens installed. A 165-kip, ±6 in. stroke hydraulic actuator was used to load the specimens. 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. The loading column transferred load through a 50-kip load cell (Figure 3.5) attached to a W10×68 wall glider that was lag bolted through a 2 in. by 8 in. No. 2 D.F. loading plate into the double top
plate of the wall. MC 6×16.3 sections on either side of the wall glider web appropriately
guided the walls to prevent out-of-plane movement. Five 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 at the first level of a
two-story home will experience, approximately 450 lbs/ft of force was imposed upon the
wall specimens by way of three structural tubes and 6-5/8 in. diameter threaded rods
anchored to the strong floor (see Figure 3.6). The 450 lbs/ft was approximated as three
point loads applied at the locations where the dead load tubes are located as shown in
Figure 3.2. The location of the dead load tubes was selected so that the tributary length
of wall for each point of load application was approximately equal. Because of this, an
equal force was applied at each location. Calibrated load cells were used to determine the
force in the rods, which were appropriately tensioned and monitored throughout testing.
The resulting horizontal resisting forces produced upon wall deflection were calculated
and subtracted from the measured lateral forces to correct the load-deflection curves. The
rods were considered flexible and their bending stiffness was neglected.

Above the loading wood, a 1/2 in. section of plywood was used so that the stucco
would not crush against the bottom flange of the wall glider once rotation of the stucco
panels occurred (see Figure 3.7). The wall glider provided a stiff boundary condition
along the top of the wall, preventing in-plane flexure of the double top plate and rocking
of the individual wall piers, modeling the relative stiffness of a second story stucco wall
and a second story floor structure above.

### 3.3 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. Stucco was placed up to
the full height of the top of the loading wood where a much more dense furring nail
spacing of 3 in. was used to create a more rigid section of stucco above the double top
plate (see Figure 3.7). This was done to simulate the continuous stucco above the second
level floor diaphragm. 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 also used at specimen ends to simulate the intersecting walls in an actual home. The boundary construction details are shown in Figure 3.8.

The interior finish of all test specimens was 1/2 in. gypsum wallboard fastened to the framing with 5d phosphate covered cooler nails spaced at 7 in. on center. 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. 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.

Two separate wall configurations were built. One wall configuration had two 4 ft by 3 ft windows, and the other configuration had one 4 ft by 3 ft window and one 2 ft-8 in. wide by 6 ft-8 in. door opening. No holdowns were installed at wall pier boundaries and no structural sheathing was installed. 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 framing elevations for all test specimens are shown in Figure 3.9. All gypsum wallboard was 4 ft by 8 ft panels. The longer length was installed horizontally and all wallboard joints were staggered (see Figure 3.10).

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. 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 listed in Table 3.2.

The exterior finish material was residential grade, Portland cement stucco. The stucco boundaries were confined by a 7/8 in. Grade 10 stucco stop commonly referred to as “J” molding because of its shape. Figure 3.11 shows the walls after application of building paper and wire lath. Figure 3.12 shows the walls after the application of the 3/8 in. brown coat, Figure 3.13 shows the walls after the 3/8 in. brown coat was applied, and
Figure 3.14 shows the final stucco product once the 1/8 in. finish coat was applied. 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 line 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)

From each coat of stucco a 2 in. diameter, 6 in. tall cylinder sample was collected for subsequent testing of compressive strength on the day of wall testing. The results are shown in Table 3.3.

3.4 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 $\Delta$ value of 1 in. was selected for all walls in this study. A graphical definition of $\Delta$ can be seen in Figure 3.15. The test results for Walls 1 and 2 show that the selected reference displacement was accurate. All tests were carried out under displacement control based on the deformation of Walls 1 and 3. Walls 2 and 4 acted as slave test specimens, which is evident when examining the wall hysteresis curves. Walls 2 and 4 typically displaced further than Walls 1 and 3 due to the geometric differences causing a difference in wall stiffness.

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2 Fiber reinforcement of stucco is a relatively recent innovation designed to control shrinkage cracking in stucco. Its use was not contemplated in the test plan, but was added to the mix by the stucco contractor in accord with his current practice. Phase 2 testing demonstrated that the addition of fiber reinforcing does not significantly alter the performance of the stucco under cyclic loading.
Figure 3.16 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 is 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 3.17 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.

### 3.5 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, strain gage rosettes, uniaxial strain gages, and inclinometers were placed in specific locations where the desired effect would be best exhibited. Table 3.4 and Table 3.5 show the individual channel descriptions for Wall 1 and Wall 2, Figure 3.18 shows the instrumentation on the face of the stucco, and Figure 3.19 shows the instrumentation attached to the wall framing. The wall panel shear deformations (WPSD channels, ±6 in.) are physically attached to the wall framing through the stucco, even though the channels are shown in Figure 3.18. All positive measurements are in the direction of the arrows for all instrumentation.

Table 3.6 and 3.7 show the instrumentation descriptions for Wall 3 and Wall 4, and Figure 3.20 and Figure 3.21 show the graphical instrumentation scheme. Figure 3.22 shows the load cell attached to each of the anchor bolts used to secure the wall specimen to the testing frame. Figure 3.23 shows an example of the strain gages that were applied to selected studs. Figure 3.24 shows an inclinometer used to measure the stucco panel
rotation and the strain gage rosettes attached to the stucco. Figure 3.25 is an example of
the linear potentiometers used to measure sill slip and sill uplift (±1.5 in.), and Figure
3.26 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
are presented in the chapters to follow. Chapter 4 covers the cyclic behavior of Walls 1
and 2, both observed and measured. All data obtained during the testing of the first set of
wall specimens will be used for the basis of comparison as the data obtained during the
testing of the second pair of wall specimens (Walls 3 and 4).
Table 3.1 Test Matrix

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<tr>
<th>Test No.</th>
<th>Specimen Designation</th>
<th>Openings</th>
<th>Testing Method</th>
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<td>Two windows</td>
<td>CUREE protocol to failure</td>
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<tr>
<td></td>
<td>2</td>
<td>One window, one door</td>
<td>CUREE protocol, 4-stage testing</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Two windows</td>
<td>CUREE protocol to failure</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>One window, one door</td>
<td>CUREE protocol, 4-stage testing</td>
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Table 3.2 Nail Geometric Properties

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<th>Length</th>
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<td>16d Common</td>
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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 3.3 Stucco Compressive Strength

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Table 3.4 Wall 1 Instrumentation

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</tr>
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</tr>
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</tr>
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<td>deformation between wall panel corners</td>
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# Table 3.7 Wall 4 Instrumentation

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(b) Anchorage to Strong Floor

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(a) Top Plate Section  (b) Typical Corner Stud Construction

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(a) Walls 1 and 3

Walls 2 and 4
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Figure 3.26  Wall Lateral Force and Shear Displacement String Potentiometers
Chapter 4  Test Results: Walls 1 and 2

4.1  Introduction

Walls 1 and 2 were tested to failure under the cyclic loading protocol described in Chapter 3. The objective was to establish baseline performance data for wall behavior in the absence of repair for comparison with the performance of repaired specimens to be presented in Chapter 5. Wall 1 had two windows, and Wall 2 had one door and one window. Both specimens were loaded and restrained along their top edge to simulate a two-story boundary condition (i.e., the walls represent the exterior first story walls in a two-story structure).

4.2  Damage State Determination

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.

The data obtained from the testing of Walls 1 and 2 was used to determine 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. Each drift level was designated as a separate stage of testing for Walls 3 and 4.

4.2.1  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.

The maximum imposed drift for each wall was plotted versus the average residual
crack widths (Figure 4.1). The average residual crack widths were also checked versus
the strength ratio for each displacement cycle to find a correlation between crack width
and the developed load (Figure 4.2). The strength ratio is defined as the maximum force
developed for each primary displacement cycle divided by the wall’s ultimate capacity.
A linear trend was assumed for both cases, which is reasonable based on the correlation
coefficient (R) computed for each least squares fit. The residual crack widths, the
strength ratios at each damage state drift level, and the relative magnitude of finish
damage were consistent with the qualitative definitions.

4.3 Definition of Response Regimes

The instrumentation described in Chapter 3 recorded wall response for the
duration of testing. By comparing various data, useful engineering quantities such as
lateral resistance, secant stiffness, and ultimate wall capacity were determined.

For ease of presentation, the response of the walls has been divided into five
regimes of behavior, identified by the maximum drift of each regime as follows:

- 0.2% drift–0.0% to 0.2% drift cycles
- 0.4% drift–0.2% to 0.4% drift cycles
- 0.7% drift–0.4% to 0.7% drift cycles
- 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 Wall 1 and approximate for Wall 2 since all testing was conducted under displacement control of Wall 1. In general, the drift of Wall 2 is greater than that of Wall 1 for each drift level. Wall behavior in each regime is presented in the following sections. Unless noted otherwise, behavior of the two walls was similar.

The global response of Walls 1 and 2 at each damage state drift level is shown in Figure 4.3 to Figure 4.5. The trailing cycles have been removed from the response plot for clarification.

4.4 0.2% Drift

Wall behavior up to 0.2% drift is characterized by a very stiff, nearly linear elastic response (see Figure 4.3) with minor cracking of finishes and no deterioration of behavior during trailing cycles. The net lateral resistance of each wall specimen is calculated by dividing the maximum applied load by the net wall length (total wall length minus wall opening widths). The net lateral resistance at 0.2% drift for Walls 1 and 2 is 942 lbs/ft and 785 lbs/ft, respectively.

The force resisted for Walls 1 and 2 was 50% of the ultimate load of each wall. Because the testing was conducted under displacement control using Wall 1, the maximum imposed displacement for Wall 1 always reflected the target level of drift. Since the wall specimens were not of equal geometry, Wall 2 always had a larger maximum imposed displacement. For the 0.2% drift cycles, Wall 1 had a maximum imposed displacement of 0.20 in. and Wall 2 had a maximum imposed displacement of 0.25 in. The corresponding residual drifts at zero wall force were 0.048 in. and 0.096 in. for Walls 1 and 2, respectively.

4.4.1 Portland Cement Plaster Damage

Stucco finish cracking produced by cyclic loading up to 0.2% is shown in Figure 4.6. 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 were measured when the wall was unloaded to zero force. It should be noted that all walls had permanent deformation in the negative direction of loading after the walls were returned to zero force. This permanent deformation is defined as residual drift. Because the
residual drift is in the negative direction, larger crack widths were measured at locations where the cracks formed during the negative displacement cycles even though the cracks that formed during the positive displacement cycles had similar maximum crack widths. (Maximum crack widths refer to the crack width measured with the wall held in a displaced position.) Because the negative direction of loading preceded returning the wall to zero force, some of the stucco cracks that formed during the positive displacement cycles were rendered unseen or had closed when observing them after the negative displacement cycles; a “CL” designates these cracks. Hairline cracks are defined as cracks that were visible at zero load but had a width of less than 0.002 in. These cracks are designated by an “HC.”

The stucco cracks that initiated at the opening corners propagated diagonally, depending on the opening location along the wall. All stucco cracks increased in length and width as the wall displacements increased up to 0.2% drift. Because the crack widths were small, the cracks are difficult to see in the photos taken. Figure 4.7(a) is an example of the stucco cracks after the walls were unloaded to zero force. (The inset shows the location where photo was taken.) A line has been drawn below the crack for visual aid. All stucco cracking was evaluated as easily repairable.

### 4.4.2 Gypsum Wallboard Damage

For the 0.2% drift cycles, very little damage occurred to the gypsum wallboard. Small hairline cracks formed near the corners of the windows and along the edges of the corner bead at various locations. Figure 4.8 shows the damage that occurred to the wallboard finish at 0.2% drift. (The dashed line indicates corner bead cracking.) Error! Reference source not found. shows initial corner bead finish cracking at the window corners. The photographs were taken at zero wall force.

### 4.5 0.4% Drift

Wall behavior from 0.2% to 0.4% drift in Figure 4.4 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 net lateral resistance for Walls 1 and 2 is 1,308 lbs/ft and 1,032 lbs/ft respectively.
The force resisted for Walls 1 and 2 was 70% and 65% of the ultimate load respectively. For the 0.4% drift cycles, Wall 1 had a maximum imposed displacement of 0.397 in. and Wall 2 had a maximum imposed displacement of 0.486 in. The corresponding residual drifts at zero wall force were 0.128 in. and 0.195 in. for Walls 1 and 2, respectively.

4.5.1 Portland Cement Plaster Damage

At 0.4% drift, stucco cracks that had developed at 0.2% drift increased in length and width. Figure 4.9 shows the stucco crack pattern for Walls 1 and 2 up to 0.4% drift. New cracks branched from the existing cracks, and at some locations the cracks propagated to the stucco boundaries. For Wall 1, the cracks that occurred at the upper window corners propagated vertically toward the stucco boundaries at the edges of the solid pier widths. The stucco cracks at the openings of the central pier edges exhibited a tendency to join the adjacent cracks that formed at the opposite opening corners. Figure 4.10 and Figure 4.11 show typical stucco cracks for both wall specimens. After this level of drift, stucco cracks formed at the stucco boundaries at wall pier edges and propagated vertically.

4.5.2 Gypsum Wallboard Damage

The gypsum wallboard cracks at all opening corners noticeably increased in length and width for both walls with respect to 0.2% drift. All wallboard cracks initiated at the ends of the corner bead and propagated at near 45-degree angle from the horizontal. The wallboard damage for Walls 1 and 2 is shown in Figure 4.12. The cracking of finish over the fastener heads was also observed up to this drift level. The fastener popping initiated at the wallboard panel edges and propagated vertically as the displacement level increased. Figure 4.13 shows the fastener popping locations for both wall specimens. A circled nail indicates a fastener pop, and the number represents the primary cycle number of displacement when the fastener pop occurred. The relative magnitude of local wallboard damage at wall opening corners is shown in Figure 4.14.

4.6 0.7% Drift

Wall behavior from 0.4% to 0.7% drift is characterized by softening of the wall stiffness (see Figure 4.5), extension of cracks in length and width, development of new
cracks, and very slight deterioration of wall response during trailing cycles. The net lateral resistance for Walls 1 and 2 is 1,682 lbs/ft and 1,361 lbs/ft respectively.

The force resisted for Walls 1 and 2 was 90% and 86% of the ultimate load respectively. For the 0.7% drift, Wall 1 had a maximum imposed displacement of 0.736 in. and Wall 2 had a maximum imposed displacement of 0.945 in. The corresponding residual drifts at zero wall force were 0.258 in. and 0.368 in. for Walls 1 and 2 respectively.

4.6.1 Portland Cement Plaster Damage

The deterioration of the stucco finish became more obvious at 0.7% drift and the crack widths and lengths were large. Figure 4.15 shows the stucco crack pattern after this level of drift. An “SP” represents locations where the stucco finish coat has flaked or spalled off the brown coat. At these locations it was difficult to take a crack width measurement. Most of the stucco cracks that originated at opening corners propagated to the stucco boundaries at the sill plate, the double 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 stucco boundaries at the stucco pier edges at both the top and bottom plates.

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. This was especially obvious in Wall 1, where the central wall pier length is 4 ft as opposed to 5 ft-4 in. for Wall 2. Figure 4.16(a) shows the typical stucco residual crack, and Figure 4.16(b) shows the typical stucco crack that had partial finish coat spalling at the opening corner. In Wall 1, corner stud twisting was observed at the wall specimen ends, and stucco cracks initiated along the height of the corner studs at the sill plate. Small relative stucco panel movement with respect to the wall framing was also noticed at this level of drift.

4.6.2 Gypsum Wallboard

The relative magnitude of damage sustained by the wallboard significantly increased between 0.4% and 0.7% 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 stucco and the gypsum wallboard, the stiffer stucco material attracted the majority of the lateral force at smaller displacement levels. As the stucco deteriorated at larger displacement levels, the gypsum wallboard attracted more force. Figure 4.17 shows the wallboard damage and crack pattern observed for Walls 1 and 2 at 0.7% drift. An increase in the number of fastener pops was also observed and shown in Figure 4.18.

For Wall 1, Figure 4.19 shows the local wallboard damage observed at the wall opening corners. At compression corners, the gypsum wallboard core crushed, which created a distributed crack pattern or rippling in the wallboard paper. 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. The local wallboard damage that occurred to Wall 2 can be seen in Figure 4.20.

### 4.7 Ultimate Strength

Wall behavior from 0.7% drift up to ultimate strength is characterized by softening of the wall stiffness (see Figure 4.21), extension of cracks in length and width, development of new cracks, and more severe deterioration of behavior during trailing cycles than previously observed. The net lateral resistance for Walls 1 and 2 is 1,880 lbs/ft and 1,590 lbs/ft, respectively which was determined using the maximum force resisted in each wall. The maximum force resisted for Walls 1 and 2 occurred at displacements of 0.97 in. and 1.10 in., respectively.

### 4.8 Failure

#### 4.8.1 Measured Response

The level of drift associated with failure had significant strength degradation past the ultimate strength of the wall, and is defined in this report as the level of drift at which the wall strength drops below 80% of the ultimate load for the first time on leading cycle. Failure of Walls 1 and 2 occurred at drifts of 1.7% and 2.0%, respectively.

Wall behavior from ultimate strength to failure is characterized by rapid softening of the wall stiffness, significant deterioration of behavior during all cycles, extensive cracking and spalling of finishes, and detachment of the stucco at the sill plate level. At failure, stucco and gypsum wallboard had large crack widths, the stucco finish coat
spalled off from the basecoats at wall opening corners, relative rotation of wall panels was observed, the cooler nails pulled through the wallboard, and the wallboard separated from the framing. Corner stud twisting, stucco panel movement relative to the framing, broken windows, and other forms of local damage were also observed. Two out of the three windows broke between drift levels of 1.5% to 2% drift. The break occurred in the fixed pane of the single-pane sliding windows.

**Global Response**

The global wall response of Walls 1 and 2 is shown in Figure 4.21. Figure 4.22 depicts the global response without the trailing cycles shown for clarity. Figure 4.23 shows the backbone curves for Walls 1 and 2, which were generated from the global wall hysteresis loops by connecting peaks of primary cycles.

The first two trailing cycles of each displacement increment were also plotted and is shown in Figure 4.24. (The dashed vertical line indicates 0.7% drift.) After 0.7% drift, a deterioration of the second trailing cycle from the first trailing cycle is still insignificant.

**Anchorage Uplift Force**

The location of the anchor bolts and designation can be seen in Figure 4.25, and the same convention is used for the remainder of the report. Figure 4.26 and Figure 4.27 show the measured uplift forces of these anchor bolts at varying levels of drift for Walls 1 and 2. The anchor bolts closest to the ends of the wall are shown since the largest forces were measured at these locations. Due to the symmetrical configuration of Wall 1, near symmetrical response of the anchor bolt force is expected, which is consistently the case for both the positive and negative displacement cycles. The slight variation between the two graphs can be attributed to the unsymmetrical placement of the anchor bolts along the length of the wall. Due to the non-symmetrical placement of anchor bolts and geometry for Wall 2, a non-symmetric anchor force distribution is expected and was measured (Figure 4.27).

The anchor bolt forces increased up to 0.7% drift, then the wall anchorage forces decreased as the wall displacement increased. This is caused by the different displacement mechanisms of the wall at different levels of drift. At lower drift levels, the walls rock similar to a rigid body. The increase in overturning created an increase in
anchorage force with increased wall displacements. Once the wall stiffness began to significantly 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 overturning force transfer to the anchor connections, thus lowering the developed force. The relative uplift force with respect to the applied lateral load in the walls was near 5% for most cases. The structure dead load, sill and stud uplift, and wall rotations and shear deformations all influence the development of anchor bolt uplift forces.

Inclinometers were placed at the mid-height of the wall piers to measure rigid body rotation of the individual stucco wall piers. Figure 4.28 shows 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 stucco panels 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.

**Wall Pier Rotation**

Figure 4.29 and Figure 4.30 show the individual stucco wall pier rotations measured along the wall at different levels of drift. For Wall 1 the wall piers rock in phase for wall displacements up to 1.0% drift. At a drift level of 1.5%, the wall pier rotations were larger at one end of the wall than at the other end, caused by the wall uplift contributing to the stucco panel rotations. The measured rotations for Wall 2 followed a similar pattern, but the slender stucco wall pier next to the door opening (Location 3) had a much larger rotation than the other wall piers above 0.7% drift. This can be attributed to the flexibility of the wall having a door opening introduced near the end of the specimen.

Large stucco cracks formed at the upper left hand corner [see Figure 4.33(b)] 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. Once the attachment at the sill plate failed, the stucco moved relative to the framing, and the measured rotations for that wall section (Location
2, 1.0% to 1.5%) did not increase, but the rotation of the end pier significantly increased and no fastener failure was observed.

As a measure of the amount of energy dissipated by the test specimens, the equivalent viscous damping at various levels of drift was computed. 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 4.31 and from Figure 4.32 it can be seen that the equivalent viscous damping ratio is near 20% for most cases.

### 4.8.2 Portland Cement Plaster Damage

The stucco crack patterns for both wall specimens at failure can be seen in Figure 4.33. The progression of stucco damage at each drift level is shown in Figure 4.34 and Figure 4.35. The cracking patterns followed the expected damage pattern for a wall with openings and the local stucco damage for Wall 1 and Wall 2 can be seen in Figure 4.36 and Figure 4.37. Figure 4.37(b) shows the joining of adjacent wall opening corner cracks for the middle wall pier in Wall 2. Figure 4.37(d) shows stucco cracking that occurred in the section beneath the window in Wall 2. Figure 4.38 shows the varying degrees of stucco damage that occurred at selected wall opening corners. Spalling of the stucco finish coat followed by crumbling of the brown and scratch coats at failure can be seen in Figure 4.38(a) and (b). Figure 4.38(c) shows the J-mold rotations at the top of the wall, which primarily occurred at wall pier edges.

The corner studs twisted at the wall ends, which created vertical cracking in the stucco along the corner reinforcement. This is shown in Figure 4.39(a). Figure 4.39(b) is an interior view of the corner stud twisting. The corner stud twisting occurred due to the eccentricity created by the difference in the strengths associated with the interior and exterior finish materials.

Figure 4.40(a) shows the crushed stucco at the sill plate level caused by the movement of the stucco relative to the framing as the stucco crushed against the instrumentation rods that were drilled into the sill plate. The large groove in the stucco
was created as the panel displaced relative to the fixed rods. Figure 4.40(b) shows the magnitude of the stucco panel displacement relative to the framing occurring at the sill plate. The large magnitude of stucco movement relative to the framing was not as obvious for Wall 1. For Wall 2, the door opening allowed for less attachment of the stucco at the sill plate, which indicated that the lack of effective attachment at the sill plate aided in the stucco movement.

Large cracks propagated toward panel boundaries and produced separate sections of stucco that rotated relative to one another. The solid stucco pier rotations were more obvious than the sections of stucco above and below wall. From Figure 4.41(a) and (b) the separation of individual sections can be seen as the large stucco cracking separates each section. Inclinometers were placed at the mid-height of each pier section so the angle of rotation could be measured. Figure 4.42 shows the measured rigid-body rotations of each individual stucco section (wall translation was not included), separated by the major cracks that formed at the opening corners. The rotations are magnified by a factor of eight for visual purposes.

4.8.3 Gypsum Wallboard Damage

The crack pattern and wallboard damage observed is shown in Figure 4.43. 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 leveled out horizontally and the majority of the damage was concentrated in the wallboard joints rather than at the wall opening corners. At wall returns, ridging of the wallboard was observed at large displacements.

The gypsum wallboard damage for Wall 1 after 1.5% drift can be seen in Figure 4.44(a) and (b). Figure 4.45 shows the local damage that occurred at Wall 1 window corners after 1.5% drift. Figure 4.45(c) shows the effect a horizontal intersecting wallboard joint had on the crack propagation that occurred near a wall opening corner. The cracks initiated at similar drift levels as other cracks, but at larger displacements the damage was concentrated in the wallboard joints rather than widening the crack.
Figure 4.46 shows the localized wallboard damage that occurred at locations other than the opening corners. The right hand side of Figure 4.46 shows the ridging occurring at the wall return caused by the restraint provided by the corner stud construction not allowing the panel to rotate further once the panel was in contact with the corner stud. Figure 4.46(b) is an example of the finish flaking at various corner bead locations. Figure 4.46(c) shows joint tape bulging, and Figure 4.46(d) shows the magnitude of damage that occurred at intersecting wallboard joints. Figure 4.46(e) shows wallboard cracking that occurred at one of the wallboard joints, which did not occur until the individual wallboard panels significantly rotated.

Figure 4.47 shows the wallboard damage that occurred to Wall 2 after 1.5% drift. Figure 4.48 shows the local wallboard damage at wall opening corners for Wall 2. The wallboard damage pattern observed in Wall 1 at this level of drift were nearly identical to those observed for Wall 2. Figure 4.48(f) shows the most dramatic case of gypsum wallboard core crushing. This location exhibited the most crushing damage because the wall pier at that end rotated more than any other pier caused by the addition of a door opening and the lack of available finish to provide resistance to rotation. Figure 4.49 shows the level of joint tape tearing observed in Wall 2 after 1.5% drift. The damage is less than that observed in the vertical joint in Wall 1 caused by the middle wall pier rotating less for Wall 2. Figure 4.50 is an example of the gypsum wallboard panel rotations observed after 1.5% drift.

As the wall displacement increased, the fastener popping became more obvious. Figure 4.51 shows the fastener popping locations, which were concentrated at the lower half of the walls. Figure 4.52 shows the wallboard fastener popping after 1.5% drift, and the various stages of fastener failure is shown in Figure 4.53. Figure 4.54 shows the buckling of a wallboard panel that has completely separated from the structural framing due to the fastener heads pulling through the paper backing of the gypsum wallboard after 2.0% drift. In Figure 4.55, the gypsum wallboard movement relative to the framing near the door opening can be seen and occurred once the wallboard panel buckled.

### 4.8.4 Observed Framing Damage

Once the testing of Walls 1 and 2 was completed, various sections of the gypsum wallboard were removed so and the condition of the framing was inspected. At wall
corner studs, permanent deformation was observed where the wall uplifted during the testing. The magnitude of residual uplift can be seen in Figure 4.56. It should be noted that no significant damage to the framing was observed as all structural framing remained sound.

Figure 4.57 shows a location at Wall 2 where building paper tearing was observed, caused by the relative movement of the stucco relative to the framing. The building paper was not observed to be torn at window or door opening locations for Walls 1 and 2.
Figure 4.1 Linear Approximation of Drift versus Residual Crack Width

Figure 4.2 Linear Approximation of Residual Crack Width versus Wall Strength Ratio
Figure 4.3  Global Response up to 0.2% Drift
Figure 4.4 Global Response up to 0.4% Drift
Figure 4.5  Global Response up to 0.7% Drift

(a) Wall 1

(b) Wall 2
Figure 4.6 Stucco Cracking pattern and Residual Crack Widths after 0.2% Drift
Figure 4.7  Wall 2 Cracking up to 0.2% Drift
Figure 4.8  Wallboard Damage up to 0.2% Drift
Figure 4.9 Stucco Cracking Pattern and Residual Crack Widths after 0.4% Drift
Figure 4.10 Wall 1 Stucco Cracking up to 0.4% Drift
Figure 4.11  Wall 2 Stucco Cracking up to 0.4% Drift
Figure 4.12 Wallboard Damage Pattern and Residual Crack Width after 0.4% Drift
Figure 4.13  Fastener Popping after 0.4% Drift
Figure 4.14  Wall 2 Wallboard Damage after 0.4% Drift
Figure 4.15 Stucco Cracking Pattern and Residual Crack Widths after 0.7% Drift
Figure 4.16  Wall 2 Stucco Cracking after 0.7% Drift
Figure 4.17  Wallboard Damage Pattern and Residual Crack Widths after 0.7% Drift
Figure 4.18  Fastener Popping after 0.7% Drift
Figure 4.19  Wall 1 Wallboard Damage after 0.7% Drift
Figure 4.19  Wall 1 Wallboard Damage after 0.7% Drift (continued)
Figure 4.20  Wall 2 Wallboard Joint Tape Tearing after 0.7% Drift
Figure 4.21  Global Wall Response with Trailing Cycles
Figure 4.22 Global Wall Response without Trailing Cycles
Figure 4.23 Wall Backbone Curves

(a) Wall 1

(b) Wall 2
Figure 4.24  Backbone Curves with Trailing Cycles
Figure 4.25  Anchorage Force Measurement Locations

(a) Wall 1

(b) Wall 2
Figure 4.26 Wall 1 Anchorage Peak Uplift Forces

(a) Positive Drift Cycles (Location 4)

(b) Negative Drift Cycles (Location 1)
Figure 4.27  Wall 2 Anchorage Peak Uplift Forces
Figure 4.28 Wall Rotation Measurement Locations
Figure 4.29  Wall 1 Peak Stucco Panel Rotations

(a) Positive Displacement Cycles

(b) Negative Displacement Cycles
Rotation (degrees)

<table>
<thead>
<tr>
<th>Drift Ratio</th>
<th>Location 1</th>
<th>Location 2</th>
<th>Location 3</th>
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<td>0.2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7%</td>
<td></td>
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</tr>
<tr>
<td>1.0%</td>
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<td></td>
</tr>
<tr>
<td>1.5%</td>
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</tbody>
</table>

Location 1
Location 2
Location 3

(a) Positive Displacement Cycles

Rotation (degrees)

<table>
<thead>
<tr>
<th>Drift Ratio</th>
<th>Location 1</th>
<th>Location 2</th>
<th>Location 3</th>
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<td>0.4%</td>
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<tr>
<td>1.5%</td>
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Location 1
Location 2
Location 3

(b) Negative Displacement Cycles

Figure 4.30 Wall 2 Peak Stucco Panel Rotations
Deformation

\[ E_D = \frac{k u_o^2}{2} \]

\[ \zeta_{eq} = \frac{1}{4\pi} \frac{E_D}{E_{so}} \]

Figure 4.31 Definition of Equivalent Viscous Damping

Figure 4.32 Equivalent Viscous Damping for Walls 1 and 2
Figure 4.33  Stucco Cracking at Failure

(a) Wall 1

(b) Wall 2
Figure 4.34 Wall 1 Stucco Damage and Residual Crack Widths

(a) 0.2% Drift
(b) 0.4% Drift
(c) 0.7% Drift
(d) Failure

Figure 4.35 Wall 2 Stucco Damage and Residual Crack Widths

(a) 0.2% Drift
(b) 0.4% Drift
(c) 0.7% Drift
(d) Failure
Figure 4.36 Wall 1 Stucco Cracking after 1.5% Drift
(a) Finish Coat Flaking  
(b) Adjacent Crack Joining  
(c) Crack Branching  
(d) Cracking beneath Window  
(e) Finish Coat Bulging  
(f) Minor Finish Coat Spalling  

Figure 4.37  Wall 2 Stucco Cracking after 1.5% Drift
Figure 4.38  Wall 1 Stucco Damage after 2.0% Drift
Figure 4.39  Corner Stud Twisting

(a) Exterior View           (b) Interior View

Figure 4.40  Wall 2 Stucco Panel Relative Movement at +2.0% Drift

(a) Base of Wall           (b) Base of Door
Figure 4.41  Wall 1 Stucco Cracking at Failure
Figure 4.42  Stucco Pier Rotations

(a) Wall 1

(b) Wall 2
Figure 4.43  Wallboard Damage at Failure
Figure 4.44  Wall 1 Wallboard Damage after 1.5% Drift
Figure 4.45  Wall 1 Wallboard Local Damage after 1.5% Drift
(a) Wallboard Ridging at Panel Boundary  
(b) Corner Bead Finish Flaking

(c) Joint Tape Bulging  
(d) Joint Tape Tearing

(e) Wallboard Cracking/Joint Tape Tearing

Figure 4.46 Wall 1 Wallboard Damage after 1.5% Drift
Figure 4.47  Wall 2 Global Wallboard Damage after 1.5% Drift
Figure 4.48  Wall 2 Wallboard Damage after 1.5% Drift
Figure 4.49  Wall 2 Joint Tearing after 1.5% Drift

Figure 4.50  Wall 2 Wallboard Panel Rotation after 1.5% Drift
Figure 4.51  Wallboard Fastener Popping Locations
Figure 4.52  Wall 2 Wallboard Fastener Popping after 1.5% Drift

Figure 4.53  Typical Wallboard Fastener Popping
Figure 4.54  Wallboard Panel Separation from Framing after 2.0% Drift

Figure 4.55  Wallboard Panel Separation at +2.0% Drift

(a) Wall 1  
(b) Wall 2

Figure 4.56  Corner Stud Uplift at Failure

Figure 4.57  Wall 2 Building Paper Tearing and Framing Condition at Failure
Chapter 5  Cyclic Behavior of Walls 3 and 4

5.1 Introduction

Testing of Walls 1 and 2 established baseline performance characteristics for cyclic loading to failure. From those tests, four performance regimes, corresponding to increasing levels of damage, were identified. The objective of testing of Walls 3 and 4 was to assess the efficacy of various repairs at each of three levels of damage. To this end, four stages of testing were performed, defined as follows:

- Stage 1: Displacement from 0.0% to 0.2% drift, repair (a)
- Stage 2: Displacement from 0.0% to 0.4% drift, repair (b)
- Stage 3: Displacement from 0.0% to 0.7% drift, repair (c)
- Stage 4: Displacement from 0.0% drift to failure (d)

Once the target level of drift for each loading stage was reached, the walls were unloaded so that the residual force in the walls was zero, and the visual condition of the wall was documented. If the walls exhibited any significant residual displacement, the walls were returned to zero wall displacement before any repairs were made. Residual stucco crack widths were documented at zero displacement so that a lower bound of residual crack widths could also be established. The damaged wall finishes were evaluated by a general contractor and repaired using a variety of repair methods.

A plot of the full loading history with milestones labeled is shown in Figure 5.1. After each stage, the walls were evaluated and repaired. During the next loading cycle, each repair was evaluated at the same drift levels to determine the repair efficacy.

In summary, Stage 1 testing involved displacement of the walls up to 0.2% drift. After testing up to 0.2% drift and the specimens unloaded, the wall finish damage was evaluated and repaired to restore the walls back to their original appearance. Stage 2 testing involved displacement of the walls up to 0.4% drift and repeating the repair process. During this stage of testing, the wall repairs performed in Stage 1 were evaluated for visual and structural performance at 0.2% drift. Stage 3 testing involved loading the walls up to 0.7% drift and repeating the repair process. During this stage of testing, the wall repairs performed in Stage 2 were evaluated for visual and structural
performance at 0.4% drift. The walls were loaded to failure in Stage 4, evaluating the performance of the Stage 3 repairs at 0.7% drift.

Performance of Walls 3 and 4 relative to the performance of Walls 1 and 2, evaluated at the end of each Stage and the repair of damage at each Stage is presented in this chapter. Efficacy of the repairs, evaluated following repeat of the damaging loading Stage is presented in Chapter 6.

The wall designations referenced in this chapter follow the nomenclature shown in Table 5.1. For example, Wall 3a represents Wall 3 that has been displaced up to 0.2% drift.

5.2 Cyclic Behavior of Walls 3a and 4a: Stage 1

Wall 3a and Wall 4a were displaced to 0.2% drift and the wall condition was evaluated.

5.2.1 Measured Response

Figure 5.2 shows the global response for Stage 1 displacement. The net lateral resistance was 1,066 lbs/ft and 921 lbs/ft for Walls 3a and 4a, respectively, at 0.2% drift. The wall response showed no stiffness or strength degradation. The residual displacement of less than 1/8 in. was considered “construction plumb.”

Wall 3a and Wall 4a anchorage uplift forces can be seen in Figure 5.3. The convention for anchor bolt force locations follows the same as the previous chapter (see Figure 4.25). For Wall 3a anchorage uplift forces, the measured force is less than 5% of the applied lateral load at 0.2% drift, and Wall 4a anchor forces are shown to be just less than 10% of the applied load for the positive displacement cycles.

The location where inclinometers were placed to measure the stucco panel rotations is shown in Figure 5.4. The stucco panel rotations can be seen in Figure 5.5. At small displacement cycles, the wall rotations are small. The wall end piers are shown to rotate more than the interior wall piers or the stucco piers above and below wall openings.

Figure 5.6 shows the stud uplift at various locations along the test specimens. Wall 3a stud uplift was measured at the interior corner stud at the ends of the wall. Wall 4a stud uplift was measured at each interior wall corner stud (studs 1 and 4) and at the door king studs (studs 2 and 3). The stud uplift for Wall 3a shows the uplift during the
positive displacement cycles being over twice the values for the negative cycles. The asymmetric anchor bolt spacing limited the sill uplift at stud 2 creating a larger stud uplift at that location. It can also be seen that for Wall 4a, the wall corner studs uplift more than the door king studs, suggesting rigid body movement of the wall specimens at small displacements.

5.2.2 Portland Cement Plaster Damage of Walls 3a and 4a

For small displacement cycles, the stucco diaphragm attracts the majority of the lateral force imposed on the wall system due to the large relative stiffness difference between the stucco and the gypsum wallboard. Stucco damage at this level is very subtle. Figure 5.7 shows the magnitude of cracking associated with Stage 1 displacement, and it can be seen that the stucco residual crack widths are very small (see Figure 5.8). Since the magnitude of stucco cracking is small, the actual cracks are difficult to observe in the photos, thus photos for all other locations are omitted for this level of stucco damage.

5.2.3 Gypsum Wallboard Damage of Walls 3a and 4a

Because the stucco attracted the majority of the force demand at this displacement level, the damage to the gypsum wallboard was limited to very small cracks forming at window and door openings. Figure 5.9 shows the general wallboard cracking pattern for Stage 1 displacement. Figure 5.10 shows the damage that occurred to Wall 3a after 0.2% drift. These figures show very small cracks originating at the wall opening corners, generally running along the corner bead. Some of the cracks are simply very small hairline cracks and at other locations the finish is shown to slightly bulge. Small cracking of the finish over a few fastener heads was also observed.

5.3 Stage 1 Wall Repairs

5.3.1 Portland Cement Plaster Repair

A local contractor recommended repair methodologies that are commonly used to repair stucco cracks of this magnitude. Table 5.2 summarizes the repair methods used and Figure 5.11 shows the locations where the specified repair method was used. For the hairline cracking (<0.002 in.), it was decided that painting would be sufficient because the crack widths were small. For the next level of stucco repair, the cracks were routed out using a grinder, then the crack was coated with an acrylic bonder and “dusted” with a
standard stucco patch and misted with water until the proper consistency and wall texture was achieved. This repair process can be seen in Figure 5.12.

To repair the larger cracks, first the stucco finish coat was ground off in a 6 in. strip around the crack and the crack was routed out along the length. Again, an acrylic bonder was applied to the crack and to the area around the crack, followed by the addition of a single layer of 4 in. wide fiberglass tape applied along the length of the crack, utilizing the acrylic bonder to adhere to the stucco brown coat. The final step involves mixing some of the stucco patch with the specified amount of water and applying it to the crack area similar to applying a stucco finish coat, then textured to match the existing stucco finish. This process can be seen in Figure 5.13. The wall was then painted to match the existing wall color once the repair was allowed to properly dry.

5.3.2 Gypsum Wallboard Repair

After a damage evaluation of the gypsum wallboard, the selected repair methods used are shown in Table 5.3 and the corresponding locations at which they were used can be seen in Figure 5.14. For small hairline cracks, painting over the cracks was selected as the preferred repair method. For the remaining cracks, three different repairs were used. The first repair involved the use of a putty knife to rout out the crack and fill it using joint compound rendering the repair unseen [Figure 5.15(a) and (c)]. Another option used was to rout out the crack and use either paper tape or fiberglass tape along the length of the crack and finish the repair with joint compound (see Figure 5.15). All fastener popping was repaired by re-setting the nail and installing an additional cooler nail at 1 in. away (see Figure 5.16) or directly on top of the existing fastener. The repair is complete after finishing the surface with joint compound.

5.4 Cyclic Behavior of Walls 3b and 4b: Stage 2

Once Stage 1 repairs were completed and cured for 48 hrs, the walls were re-tested from the beginning of the loading protocol up to the target displacement of 0.4% drift for Stage 2.

5.4.1 Measured Response of Walls 3b and 4b

The global wall response is shown in Figure 5.17. The net lateral resistance for Walls 3b and 4b was 1,390 lbs/ft and 1,145 lbs/ft, respectively. From the hysteresis plots
it can be seen that minor wall softening has occurred. The wall force developed is roughly 80% of the ultimate capacity\textsuperscript{3}.

The measured anchor uplift forces for various levels for Wall 3b and Wall 4b are shown in Figure 5.18. The notation used is such that the first number represents the reference specimen and the second number refers to the anchor location along the walls as previously mentioned. The developed anchorage uplift forces at 0.2% drift are also shown.

The individual stucco wall panel rotations are shown in Figure 5.19. As expected, the more slender wall piers located at the wall ends showed a larger measured rotation than the interior wall piers for both levels of drift compared. This trend is consistent for both wall specimens. The measured rotations of the small wall panels above and below the window openings are smaller than the measured rotations for the longer wall piers for Wall 3b. Wall 4b shows the same trend, as the individual wall panels above and below the window and door openings rotate less than the solid wall piers of the wall for the two levels of drift measured.

Figure 5.20 shows the peak stud uplifts recorded during Stage 2 displacement. The stud uplift for both walls increased with increasing wall displacement, and Wall 4b corner stud uplifts were larger than the uplift measured at the door king studs, which implies that the wall panel is still reasonably acting as a rigid body.

### 5.4.2 Portland Cement Plaster Damage

The typical stucco cracking patterns and corresponding major crack widths observed at the end of Stage 2 displacement can be seen in Figure 5.21. The crack widths were measured while the walls were held at the target displacement (values shown in parenthesis) and also measured after the wall forces were reduced to zero load. At this level of displacement, all wall opening corners had obvious measurable crack widths.

The Stage 1 repairs did not change the crack pattern observed in the repaired walls, since the stucco cracking essentially followed the same path as the repaired cracks. Depending upon the repair method used, the localized cracking patterns changed slightly;

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\textsuperscript{3} After the negative displacement cycle reached the target displacement of –0.4% drift, data acquisition was not reactivated immediately following the documentation process and this can be seen on the hysteresis loops where a straight line exists on the negative displacement side.
the effects of which will be discussed in Chapter 6.

At some locations, the cracks propagated to the stucco boundaries and secondary cracks branched off the primary cracks. All cracks noticeably increased in width and length as the wall displacements increased and new cracks formed at the stucco boundaries at the edges of the wall piers. The cracks that occurred at the adjacent opening corners of the central wall piers showed a tendency to join and did join in Wall 3b. For this wall, Figure 5.21 graphically shows the Stage 2 crack pattern and Figure 5.22 shows the typical Stage 2 stucco cracking.

5.4.3 Gypsum Wallboard Damage

The Stage 2 wallboard damage was limited to measurable cracking at the wall opening corners and joint tape damage. Corner bead cracks and fastener popping were also observed at this level of drift. The wallboard damage is shown in Figure 5.23. The local damage was dependent on the Stage 1 repair method used at various wall locations. Figure 5.24 shows cracks that occurred at previously repaired cracks, where the cracks were routed out with a putty knife and finished over with joint compound. Some slight bulging of the paper tape used in Stage 1 repairs was also observed.

Figure 5.25 shows the typical corner bead cracking that occurred in Stage 2. Figure 5.26 shows the typical joint damage that occurred in Stage 2 due to the relative wallboard rotation of the individual panels, and Figure 5.27 shows the corner bead buckling and subsequent finish bulging.

5.5 Stage 2 Wall Repairs

5.5.1 Portland Cement Plaster Repair

After evaluating the stucco damage, the repair methods outlined in Table 5.4 were used to repair the damaged walls once the walls were returned to a plumb position. The corresponding locations where each repair method was used can be seen in Figure 5.28. Similar to the Stage 1 repair method, the stucco finish coat was ground off and the cracks were routed out using a diamond grinder. An acrylic bonder was then applied to the stucco brown coat and strips of 4 in. wide fiberglass tape were applied over the length of the crack. Next, a cementitious bonding agent was applied in a thin layer so that the crack could be filled and the fiberglass tape could be embedded into the bonding agent
(see Figure 5.29). Once dry, a stucco finish coat supplemented with an acrylic-bonding agent was applied and textured to match the existing wall finish.

Another Stage 2 repair method was the addition of 2-1/2 in. deck screws spaced at 12 in. on center at the bottom perimeter (at the sill plate level) of the wall. The screws were counter-sunk to facilitate patching (see Figure 5.30). The purpose of the deck screws was to restore stiffness to the walls and limit the stucco movement relative to the framing at large displacements.

### 5.5.2 Gypsum Wallboard Repair

After the damage evaluation of the gypsum wallboard, the repair methods outlined in Table 5.5 were implemented at the locations shown in Figure 5.31. At locations where the cracking was the least severe, the cracks were routed out (see Figure 5.32) and filled with joint compound. If the wallboard damage occurs at a location where repair tape was used for a previous repair, the condition of the repair tape was evaluated and the tape was either removed or left in place depending on the level of damage (see Figure 5.33). At locations where any visible damage to the previous repair tape was evident, the tape was stripped and replaced (see Figure 5.34 and Figure 5.35).

Where any significant corner bead cracking or joint tape tearing was observed, the damaged finish and/or tape was stripped off and 1-1/4 in. wallboard screws were installed at 7 in. on center. Fiberglass repair tape was then applied to the damaged area and finished with setting-type joint compound (see Figure 5.34, Figure 5.36, and Figure 5.37).

A supplemental repair of 1-1/4 in. drywall screws applied along the bottom and side perimeter of the walls at 7 in. on center is shown in Figure 5.38. The primary objective was to restore any loss of stiffness at this level of displacement. For any fastener popping, the nails were reset and an additional 1-1/4 in. drywall screw was installed at 1 in. away (see Figure 5.39).

### 5.6 Cyclic Behavior of Walls 3c and 4c: Stage 3

Once Stage 2 repairs were completed and cured for 48 hrs, the walls were re-tested from the beginning of the loading protocol up to the target displacement of 0.7% drift for Stage 3.
5.6.1 Measured Response

The global response of Walls 3c and 4c is shown in Figure 5.40. The walls experienced some stiffness degradation at this level of drift, and the applied lateral loads reached about 90% of ultimate wall capacity. Figure 5.41 and Figure 5.42 show the peak anchorage uplift forces recorded at the ends of each wall panel at each damage state drift level. The anchorage uplift forces all increased with increased wall displacements for both positive and negative displacement cycles. This was expected due to the increase in overturning; however, the magnitude of the negative displacement cycle anchorage uplift forces are less than the values recorded for the positive displacement cycles. When comparing the two wall configurations, the peak forces developed during the positive and negative cycles are similar, indicating that the addition of a door versus a window opening has little effect on the shear wall mechanics up to this level of displacement.

Figure 5.43 shows the peak individual stucco panel rotations. The trend was similar to that observed in Stage 2 test. The measured stud uplift values for Stage 3 are shown in Figure 5.44. The corner stud uplift for Wall 3c is larger for the positive displacement cycles than for the negative displacement cycles, whereas the corner stud uplift recorded for Wall 4c positive and negative displacement cycles are similar for all levels of drift. The corner stud uplift values for Wall 4c are consistently larger than the uplift measured at the door king studs. This difference gets larger as the wall displacements increase.

5.6.2 Portland Cement Plaster Damage

The stucco crack pattern and measured crack widths for Wall 3c and Wall 4c are shown in Figure 5.45. The cracking at the wall opening corners reopened along the repaired crack lengths. The crack widths were often difficult to measure at various locations because the fiberglass tape and finish coat bulged from the stucco base coats. The bulging of the finish coat and fiberglass tape used for the previous repairs masked the true crack widths and lengths at this level of displacement. Figure 5.46 shows the magnitude of the stucco cracks observed at the locations noted for Wall 3c.

Figure 5.47 shows the finish coat bulging that occurred at Wall 4c opening corners that resulted from the fiberglass tape and dry bond not being adequately bonded.
to the stucco brown coat. Minimal finish coat spalling was observed since the finish coat adhered to the fiberglass tape and dry bond coat.

Figure 5.48 shows the stucco cracks that initiated at repair screw locations. For both wall specimens, rather than one large primary crack originating at wall opening corners and branching off, numerous cracks were observed at various opening corners, which resulted from the previous stucco repair and the flexibility of the fiberglass tape.

5.6.3 Gypsum Wallboard Damage

The gypsum wallboard sustained more damage at the same levels of drift than previously observed. The addition of the 1-1/4 in. drywall screws at the damaged joints, corner bead, and wall perimeter for the Stage 2 wallboard repair significantly stiffened the wallboard at small displacements. The addition of supplemental screw fasteners to the gypsum wallboard held the wallboard panels to the structural framing much more securely than with the 5d cooler nails alone. Because of the increase in initial stiffness, the walls attracted more force at the same level of displacement when compared to previous tests.

For example, joint tape damage was observed at Stage 1 drift (0.2%) while no joint damage was observed until Stage 2 drift for previous tests. Figure 5.49 shows the gypsum wallboard damage observed after Stage 3 drift of 0.7%. Joint tape damage and finish bulging and cracking were the most prevalent forms of damage observed. Fastener popping was significantly reduced by the addition of supplemental screws and other forms of damage became more prevalent than previously observed.

Figure 5.50 shows the various forms of wallboard damage observed for Stage 3 drift. Figure 5.50(a) shows the bulging of the finish applied to a routed crack. The slight bulging is a direct result of repairing and repainting after each repair. Figure 5.50(b) shows the damage that occurred at an opening corner where paper tape was used to repair a previous crack. Cracking initiated along the sides of the paper tape, then propagated at a 45-degree angle. Once the cracking extended beyond the paper tape, the paper tape began to separate and bulge at larger displacements. Figure 5.50(c) is an example of a location where the crack simply reopened along the length where no repair tape was used for a previous repair.
Figure 5.51 shows a location where fiberglass tape was previously used for crack repair. The finish bulged, or buckled as the crack propagated beneath the repair tape. The fiberglass mesh of the repair tape is shown once the finish over the fiberglass tape flaked off. Joint tape damage was also observed and the general magnitude of joint damage that occurred can be seen in Figure 5.52.

The occurrence of fastener popping was significantly reduced at Stage 3 drift compared to that previously observed at Stage 3 drift in Walls 1 and 2. Figure 5.53 shows a location at the sill plate level where a new form of fastener damage was observed. The cracking and breaking of the gypsum wallboard at the panel edges was caused by the larger force demand on the fasteners at the wallboard panel boundaries. Previously shown in the Chapter 4, the fasteners at these locations would fail by pulling through the wallboard paper. After the installation of the screws, the force demand on the fasteners at these locations increase due to the increase in stiffness, and the strength of the gypsum at the wallboard edges was not large enough to resist the imposed forces.

5.7 Stage 3 Wall Repairs

5.7.1 Portland Cement Plaster Repair

Once the damaged stucco was evaluated, it was decided that the Stage 2 crack repair specification would be used for all Stage 3 stucco crack repairs. The locations of the crack repair are noted in Figure 5.54. Figure 5.55 shows the grinded off finish coat and routed stucco cracks, and Figure 5.56 shows some routed cracks with the acrylic bonder applied to the stucco brown coat for Wall 3c. Figure 5.57 shows the dry bond application and Figure 5.58 shows the completed stucco repair with the textured finish coat.

5.7.2 Gypsum Wallboard Repair

After a damage evaluation of the gypsum wallboard was performed for the Stage 3 drift, the repair methods outlined in Table 5.7 were implemented. The corresponding location where the specified repair method was used is shown in Figure 5.59. Figure 5.60 shows various locations where the wallboard cracks were routed out prior to fiberglass tape application. Figure 5.61 shows a location where either the corner bead and/or existing repair tape was stripped and replaced with fiberglass tape along the length of the damage. Figure 5.62 shows the stripped wallboard joints and fiberglass tape
application before the finish or joint compound is used to complete the repair. Figure 5.63 shows a location where the wallboard was sufficiently damaged to merit the removal and replacement of a portion of the wallboard. Figure 5.64 shows the replaced section of wallboard, fastened to the framing using 1-1/4 in. wallboard screws at 7 in. on center and having the new panel edges finished with fiberglass tape and setting-type joint compound.

5.8 Cyclic Behavior of Walls 3d and 4d: Stage 4

Once Stage 3 repairs were completed and cured for 48 hrs, the walls were re-tested from the beginning of the loading protocol to failure.

5.8.1 Measured Response

The global hysteresis of the wall specimens can be seen in Figure 5.65. It can be seen that the capacity of the walls occurs at a drift of 1 to 1.5% for both wall configurations, and failure typically occurs between 2 to 2.5% drift. Wall capacities were 15.6 kips and 15.0 kips for Walls 1 and 2, respectively. Residual drifts were significant at this level and were measured to be near 1-3/4 in.

The exterior and interior wall finishes were badly damaged and could no longer effectively transmit the imposed lateral force to the sill of the walls. This can be seen when examining the anchorage forces developed at each drift level (see Figure 5.66 and Figure 5.67). Wall 3d best exhibited this effect, since at levels close to the drift when the maximum strength was reached the anchorage forces are highest, suggesting that the force transfer from the loading beam to the sill plate is effective up to a drift level near the wall capacity. At levels of drift beyond the wall capacity, the force transfer mechanisms no longer functioned at a desired performance level, evident from the decrease in anchorage force. Wall 4d exhibits similar behavior for the positive displacement cycles. The negative displacement cycles are also very similar, but the door opening affected the force transfer for the negative direction. The anchorage uplift forces at the wall corners were typically less than 7% of the developed wall forces at all drift levels. The imposed dead load and panel orientations affect the amount of force developed in overturning at the wall corners, and the anchorage forces measured at the wall corners were typically higher than at any of the other anchor bolt locations.
An attempt to predict the measured anchorage forces was made, but the indeterminacy of the structure and missing anchor bolt uplift forces\(^4\) hindered the process. Because three out of the four anchorage uplift forces were recovered for Walls 1 and 3, the negative displacement cycles were the focus for determining a procedure for the prediction of anchorage uplift forces.

A free-body diagram of Walls 1 and 3 is shown in Figure 5.68. Because the force at channel “WWAF3” was not recorded [see Figure 3.19(a)], a simplified free-body diagram was assumed and can be seen in Figure 5.69. The simplification involved the assumption that two of the anchor bolts were in tension and the other two anchor bolts were in compression at small displacement levels. This assumption allowed the compression force to be determined by summing the forces in the vertical direction. The corresponding location of the compression resultant force, \(C\), from the end of the wall labeled as “\(x\)” was then computed by summing moments about the end of the wall. As the imposed displacements increased, \(x\) decreased. At drifts of 0.7% and larger, \(x\) was essentially located at the wall end, indicating that the wall was rotating about one end as the forces in the walls approached the ultimate strength. An attempt to predict the anchor bolt forces at ultimate strength was made, but the predicted forces were nearly 2.5 times the measured forces for Walls 1 and 3 and can be seen in Figure 5.70.

The measured anchorage uplift forces were consistently slightly larger at WWAF2 than WWAF1. This is not surprising when the relative rigidity of each main stucco pier is considered. The location of WWAF2 is such that the larger force attraction is to the central pier, which increases the overturning at the end of the central with respect to the end of the wall. This was verified by checking the sill uplift recorded at the end of the wall and at the end of the central pier near the location of WWAF2, and the sill uplift was consistently larger at that location.

Figure 5.71 shows the individual stucco panel rotations along each wall. For Wall 3d, it can be seen that the individual wall panel sections above and below the window openings rotate significantly less than the solid wall pier sections. All main wall pier sections rotated in phase for all levels of drift. For Wall 4d, it can be seen that the main

\(^4\) Due to constraints in the number of available load cells to measure the anchorage uplift forces or damage occurring to the wiring of the load cells, not the anchorage forces of all anchor bolts were recovered.
individual stucco piers rotate significantly more than the wall panels above and below any wall opening. This is especially obvious at larger displacements. Again as expected, the slender more flexible wall piers at the ends of the wall rotate more than the middle stucco pier.

Figure 5.72 shows the stud uplift at the corner studs for each wall for Wall 3d and Wall 4d. Wall 3d had a maximum stud uplift of roughly 15% of the imposed drift, with the maximum value occurring between 1.5% to 2.5% drift for the negative displacement cycles. The stud uplift values for the positive displacement cycles were roughly 50% of the values measured during the positive displacement cycles. Wall 4d maximum stud uplift values occurred during the positive displacement cycles of 1.5% to 2.5% and ranged between 17% to 20% of the imposed drift. The measured king stud uplifts at the door opening are smaller than the wall corner stud uplift for all levels of drift, again enforcing the notion that the walls displace more as a rigid body than as a individual wall pier sections.

5.8.2 Portland Cement Plaster Damage

The stucco cladding experienced major damage at large displacement levels. The crack widths were not measured for levels of drift past 0.7% because the cracks were so large and the stucco damage was so widespread at failure that measuring the crack widths would not provide much useful information. Another factor that inhibited the measuring of the crack widths involved the bulging of the finish coat over the fiberglass repair tape. The bulge masks the true structural crack observed at comparable levels of drift. The crack widths were measured for all relevant levels of drift for the other Stages previously discussed.

Figure 5.73 shows the stucco crack patterns observed at failure. The fiberglass repair tape and finish coat buckled at nearly all wall opening corners. At some locations, the fiberglass tape tore along the length of the crack and at other locations the fiberglass tape only bulged. The window opening corners adjacent to the middle wall pier had cracks that joined and became very large at large displacements, with much more severe cracks observed at the lower opening corners. Figure 5.74 shows the stucco damage sustained by Wall 3d. It can be seen that the fiberglass tape and the finish coat has
separated from the brown coat as the cracks beneath the repair became large. This was more apparent after the removal of the stucco finish coat and repair tape.

At some locations the fiberglass tape fractured along the length of the crack and at other locations, the fiberglass tape separated from the brown coat and bulged out in compression. Figure 5.75(a) shows the tendency of the corner stud to twist at large displacements, evident by the stucco cracks at the wall corners, and Figure 5.75(b) shows the stucco cracks at the bottom of the sill plate, which originated at the repair screws at various locations.

The damage sustained by Wall 4d is similar to the damage in Wall 3d with some local variation and can be seen in Figure 5.76 and Figure 5.77. Figure 5.76 shows the large stucco cracks observed before and after the removal of the repair tape after 2.5% drift. The fiberglass repair tape ripped along the length of the crack since the dry bond adhered well with the tape and the stucco brown coat. In other locations the bond was not as good, and the fiberglass tape and finish coat bulged and separated from the brown coat. The wire lath fractured at some locations [see Figure 5.76(c)], and at other locations the stucco base coats crumbled from the wire lath. Figure 5.77(a) shows the stucco cracking that initiated at the repair screws, and Figure 5.77(b) shows the continuous cracks that formed at the sill plate level, connecting all the repair screws into one large crack. Even though a large amount of cracking was observed at the sill plate level, very little stucco panel relative movement was observed.

5.8.3 Gypsum Wallboard Damage

The general gypsum wallboard damage for Wall 3d and Wall 4d followed the previously observed damage patterns, but some of the repair methods did significantly affect the local damage at wall opening corners. Figure 5.78 shows the global damage sustained by the gypsum wallboard at failure.

The wallboard damage observed was similar for all levels of loading. The only difference was the observed level of finish bulging and flaking that increased when compared with equivalent levels of drift. This was because the walls have been repaired three separate times previously before loaded to failure. Some of the finish was stripped at some repair locations and not at others, depending on the repair. If these locations only had the crack routed out and repaired with tape, the finish thickness increases. The walls
have also been repainted after each level of loading which adds another layer of paint after each repair.

Figure 5.79 to shows the various damage that occurred to the wallboard after 2.5% drift. Figure 5.79(a) shows the finish bulging close to the corners where significant repairs had taken place. Further away from the area that gets built-up with finish, the wallboard cracking can be seen more clearly than in the vicinity of the corner where the wallboard cracking beneath the finish causes the finish to bulge with the fiberglass repair tape. This large amount of bulging was not observed to occur until after 0.7% drift was achieved.

Figure 5.80(a) shows the magnitude of joint tape damage that occurred to the wallboard joints located at the central pier. The same flaking of wallboard finish over the fiberglass tape was observed. The repair method of removing and replacing a portion of the wallboard provided the most drastic difference in damage with respect to all other repair methods used. The magnitude of the observed damage at the same drift levels was significantly changed at the locations where this repair method was used. Instead of the majority of damage concentrating in wallboard cracks at these locations, the new wallboard joints created at these locations caused the majority of the damage to be concentrated in the joints rather than at the opening corners. This was common to all locations where this repair was used and can be seen in Figure 5.80(b).

5.8.4 Observed Framing Damage

Once the testing of Walls 3 and 4 was completed, various sections of the gypsum wallboard were removed so and the condition of the framing was inspected. Framing damage was similar to that observed in Walls 1 and 2.
Table 5.1 Damage State Drifts

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<tr>
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Table 5.2 Stage 1 Stucco Repair Methodologies

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<tr>
<td>2</td>
<td>Rout and fill cracks</td>
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</tr>
<tr>
<td></td>
<td>• Acrylic bonder</td>
<td></td>
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<tr>
<td></td>
<td>• Stucco patch</td>
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</tr>
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<td>3</td>
<td>Rout and fill cracks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Grind off finish coat</td>
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</tr>
<tr>
<td></td>
<td>• Acrylic bonder</td>
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</tr>
<tr>
<td></td>
<td>• Fiberglass tape</td>
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</tr>
<tr>
<td></td>
<td>• Stucco patch</td>
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Table 5.3 Stage 1 Gypsum Wallboard Repair Methodologies

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</tr>
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<td>Rout and fill cracks</td>
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<td>• Joint compound only</td>
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<td>Rout and fill cracks</td>
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<td>• Fiberglass tape</td>
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<td>• Reset nail pops</td>
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<td>• Additional fastener at 1 in. away</td>
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Table 5.4 Stage 2 Stucco Repair Methodologies

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<tr>
<td></td>
<td>• Add Acrylic bonder</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Apply Fiberglass tape</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Apply Dry Bond</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Apply Finish coat</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Provide 2-1/2 in. deck screws @ 12 in. o.c. to bottom perimeter</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.5  Stage 2 Gypsum Wallboard Repair Methodologies

<table>
<thead>
<tr>
<th>Location</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rout and fill cracks</td>
</tr>
<tr>
<td>2</td>
<td>Strip any existing repair tape, replace with fiberglass tape, finish</td>
</tr>
<tr>
<td>3</td>
<td>Strip any existing repair tape, replace with paper tape, finish</td>
</tr>
<tr>
<td>4</td>
<td>Strip damaged joint tape, add 1-1/4 in. screws to joint, apply fiberglass tape, finish</td>
</tr>
<tr>
<td>5</td>
<td>Strip damaged corner bead, install 1-1/4 in. screws</td>
</tr>
<tr>
<td>6</td>
<td>Install 1-1/4 in. screws 7 in. o.c. along perimeter of walls</td>
</tr>
</tbody>
</table>

Reset fastener popping and add 1 1/4” screw @ 1 in. away

Table 5.6  Stage 3 Stucco Repair Methodologies

<table>
<thead>
<tr>
<th>Location</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>California Plastering</td>
</tr>
<tr>
<td></td>
<td>Consultants Specification:</td>
</tr>
<tr>
<td></td>
<td>• Grind finish coat</td>
</tr>
<tr>
<td></td>
<td>• Rout cracks</td>
</tr>
<tr>
<td></td>
<td>• Acrylic bonder</td>
</tr>
<tr>
<td></td>
<td>• Fiberglass tape</td>
</tr>
<tr>
<td></td>
<td>• Dry Bond</td>
</tr>
<tr>
<td></td>
<td>• Finish coat</td>
</tr>
</tbody>
</table>

Table 5.7  Stage 3 Wallboard Repair Methodologies

<table>
<thead>
<tr>
<th>Location</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Strip existing corner repair tape, replace</td>
</tr>
<tr>
<td>2</td>
<td>Strip damaged joint tape, replace</td>
</tr>
<tr>
<td>3</td>
<td>Remove and replace damaged wallboard, screw</td>
</tr>
<tr>
<td>4</td>
<td>Strip finish at corner bead, re-tape</td>
</tr>
</tbody>
</table>

Reset and finish all fastener popping
Figure 5.1  Loading Protocol and Loading Stages
Figure 5.2 Stage 1 Global Response (Walls 3a and 4a)
Figure 5.3  Anchorage Peak Uplift Forces at Stage 1 Drift

Anchor Force Location

(a) Wall 3a

(b) Wall 4a
Figure 5.4 Wall Rotation Measurement Locations
Figure 5.5 Peak Wall Stucco Panel Rotations at Stage 1 Drift
Figure 5.6  Stud Uplift at Stage 1 Drift
Figure 5.7  Stage 1 Stucco Cracking
Figure 5.8 Wall 4a Stucco Cracking at Stage 1 Drift
ALL HAIRLINE CRACKS

(a) Wall 3a

ALL HAIRLINE CRACKS (U.N.O.)

(b) Wall 4a

Figure 5.9 Stage 1 Wallboard Damage
Figure 5.10  Wall 3a Wallboard Damage at Stage 1 Drift
Figure 5.11 Stage 1 Stucco Repair Locations (see Table 5.2)
(a) Routed Stucco Crack  
(b) Acrylic Bonder Application 

(c) Stucco Patch Application

Figure 5.12 Stage 1 Stucco Repair Method 2
(a) Ground Off Finish Coat and Routed Stucco Crack

(b) Acrylic Bonder Application

(c) Fiberglass Tape Application

(d) Stucco Patch Application

(e) Completed Repair

Figure 5.13 Stage 1 Stucco Repair Method 3
Figure 5.14 Stage 1 Wallboard Repair Locations (see Table 5.3)
Figure 5.15  Stage 1 Wallboard Repair Method 3

(a) Routed Wallboard Crack  
(b) Fiberglass Tape Application  
(c) Completed Repair

Figure 5.16  Wallboard Fastener Popping Repair

(a) Repair  
(b) Completed repair
Figure 5.17  Stage 2 Global Wall Response (Walls 3b and 4b)
Figure 5.18  Anchorage Peak Uplift Forces for Stage 2 Drift
Figure 5.19  Peak Stucco Wall Panel Rotations at Stage 2 Drift

(a) Wall 3b

(b) Wall 4b
Figure 5.20  Peak Wall Stud Uplift for Stage 2 Drift

(a) Wall 3b

(b) Wall 4b
(a) Wall 3b

(b) Wall 4b

Figure 5.21 Stage 2 Stucco Cracking
Figure 5.22  Wall 4b Stucco Cracking at Stage 2 Drift
Figure 5.23  Stage 2 Wallboard Damage
Figure 5.24 Wall 3b Wallboard Damage at Stage 2 Drift
Figure 5.25  Wall 4b Wallboard Damage at Stage 2 Drift
Figure 5.26  Wall 3b Joint Tape Tearing/Ridging at Stage 2 Drift

Figure 5.27  Wall 4b Wallboard Damage at Stage 2 Drift
Figure 5.28  Stage 2 Stucco Repair Locations (see Table 5.4)
(a) Dry Bond and Fiberglass Tape

(b) Finish Coat Application

Figure 5.29  Stage 2 Stucco Repair Method

Figure 5.30  Wall 3b Deck Screw Installation at Wall Bottom Perimeter
Figure 5.31 Stage 2 Wallboard Repair Locations (see Table 5.5)
Figure 5.32  Wall 3b Routed Wallboard Crack

Figure 5.33  Wall 3b Paper Tape Application

Figure 5.34  Wall 3b Corner Bead/Joint Tape Finish Stripping

Figure 5.35  Wall 3b Corner Bead Stripping/Existing Repair Tape Removal
Figure 5.36  Wall 4b Corner Bead/Joint Tape Finish Stripping

Figure 5.37  Wall 4b Screw Installation at Corner Bead/Wallboard Joint

Figure 5.38  Wall 4b Wallboard Perimeter Screw Installation

Figure 5.39  Wall 4b Reset Fastener with Screw Installed 1 in. Away
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Figure 5.41  Wall 3c Anchorage Peak Uplift Forces
Figure 5.42  Wall 4c Anchorage Peak Uplift Forces

(a) Positive Displacement Cycles

(b) Negative Displacement Cycles
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Figure 5.44 Stud Uplift at Stage 3 Drift
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Figure 5.46  Wall 3c Stucco Cracking
Figure 5.46  Wall 3c Stucco Cracking (continued)
Figure 5.47  Wall 4c Finish Coat Bulging
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(b) Repair Tape Bulging

(c) Reopened Finish Crack

Figure 5.50  Wall 3c Wallboard Damage
Figure 5.51  Wall 4c Wallboard Damage

Figure 5.52  Wall 3c Joint Tape Tearing

Figure 5.53  Wall 3c Wallboard Fastener Damage
Figure 5.54 Stage 3 Stucco Repair Locations (see Table 5.6)
(a) Ground Finish Coat

(b) Routed Stucco Cracks

Figure 5.55  Wall 3c Ground Finish Coat/Routed Stucco Cracks

Figure 5.56  Wall 3c Routed Stucco Cracks/Acrylic Bonder Application

Figure 5.57  Wall 3c Dry Bond Application

Figure 5.58  Wall 4c Dry Bond and Finish Coat Application
Figure 5.59  Stage 3 Wallboard Repair Locations (see Table 5.7)
Figure 5.60  Wall 3c Routed Wallboard Crack
Figure 5.61  Wall 4c Stripped Wallboard Finish/Fiberglass Tape Application

Figure 5.62  Wall 3c Stripped Wallboard Joint Tape

Figure 5.63  Wall 4c Removal of Damaged Portion of Wallboard
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Figure 5.69  Walls 1 and 3 Simplified Free Body Diagram
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Figure 5.72  Peak Wall Stud Uplift at Failure
Figure 5.73  Stucco Cracking at Failure
before Finish Removal  ←  →  after Finish Removal

(a) Left Window, Lower Left Corner

(b) Left Window, Lower Right Corner

(c) Right Window, Lower Left Corner

Figure 5.74  Wall 3d Stucco Damage after 2.5% Drift
before Finish Removal ← → after Finish Removal

(d) Right Window, Lower Right Corner

Figure 5.74  Wall 3d Stucco Damage after 2.5% Drift (continued)

Figure 5.75  Wall 3d Stucco Damage after 2.5% Drift
Figure 5.76  Wall 4d Stucco Damage after 2.5% Drift
Figure 5.77  Wall 4d Stucco Damage after 2.5% Drift
Figure 5.78 Wallboard Damage at Failure
before Finish Removal  ← →  after Finish Removal

(a) Wall 3d, Right Window Opening

(b) Wall 3d, Left Window Opening

(c) Wall 4d, Window Opening

Figure 5.79  Wallboard Damage after 2.5% Drift
Figure 5.80  Wallboard Damage after 2.5% Drift
Chapter 6  Comparison of Test Results

6.1 Introduction

To determine the efficacy of the repair methodologies used at the various damage states, comparisons are made between the performance of the specimens tested without repair (Walls 1 and 2) and specimens repaired at each stage of loading (Walls 3 and 4). Additionally, the performance of Walls 3 and 4 in both the unrepaired and repaired condition is compared at the same stage of loading.

Each of the repair methods used for this project has inherent advantages and disadvantages. The following sections provide an evaluation of the various repair methods used. For structural evaluation, various structural properties such as resistance and stiffness of the walls will be investigated in accordance with localized effects exhibited at various wall locations. For aesthetic evaluation, the wall finishes at all repair locations will be compared at the same drift levels. The global damage patterns will also be addressed.

6.2 Performance at 0.2% Drift: Stage 1 Repairs

6.2.1 Measured Performance Comparison

For Stage 1 damage, the repair methods used for both the interior and exterior finish are considered minor repairs. Figure 6.1 shows the backbone curves for the original wall and the repaired wall at the same level of drift. The trailing cycles of Walls 3a and 4a are also shown. The backbone curves of the trailing cycles represent the response of the walls if they had been reloaded without any repair. The difference between the trailing cycles and the repaired walls shows that repairing the walls increased the resistance and stiffness at equivalent levels of drift.

At such small displacements, both walls performed well. Less than a 5% resistance reduction was observed between the original and the repaired walls at the 0.2% drift. A slight unrecoverable loss of stiffness was present, but the difference was considered negligible at this displacement level since the wall stiffness and resistance at the end of the Stage 1 drift level is nearly the same. The structural fasteners bearing against the finish materials and damaging the original bond caused the slight stiffness
variation. Upon reloading, this difference is insignificant when considering the effect on the wall performance above 0.2% drift.

The residual displacements for all walls tested at the Stage 1 damage state can be seen in Figure 6.2. The average residual drift measured for all walls is roughly 50% of the imposed level of drift.

The average residual crack widths for all tests at the Stage 1 damage state drift are shown in Figure 6.3. For the Stage 1 damage repairs (a versus b.a), the crack widths for Wall 4 were reduced and the level of magnitude of the measured cracks for Wall 3 is essentially the same.

Figure 6.4 shows the peak anchor bolt uplift forces recorded at the ends of each wall for 0.2% drift for all wall specimens that were repaired. The same anchorage forces were not developed at 0.2% drift for all wall specimens that had an imposed drift of 0.4% or greater.

The equivalent viscous damping for the original and the repaired walls was similar as shown in Figure 6.5, and the amount of energy dissipated was the same.

The observed structural performance of the repaired walls with respect to the original walls was acceptable at this level of drift. The repair methods used at the Stage 1 damage state achieved a comparable structural performance level for the repaired wall specimens.

### 6.2.2 Portland Cement Plaster Damage Comparison

The level of damage sustained by the stucco cladding is considered minimal for this level of drift. The stucco cracking at this drift was very small. Figure 6.6 shows the stucco cracking for the original walls and the repaired walls after 0.2% drift. The crack patterns are nearly identical for both cases. Aesthetically, the walls performed the same for each repair method used. For the locations where painting was the preferred repair method, the cracks simply opened along the identical path once the bond between the paint and the crack was broken and the crack widths were slightly widened. Figure 6.7 shows a location where paint was used to cover the crack and it can be seen that the cracking is nearly identical.

Figure 6.8 shows a comparison of repair method 2 at the Stage 1 damage state. The crack tended to follow the repaired crack path and slightly branched off at one
location. The crack width was reduced from 0.009 in. to 0.005 in. Figure 6.9 shows the repair of the larger stucco crack using repair method 3. At this location, the crack width slightly increased, but the length was reduced. All stucco repair methods produced favorable results and can be considered effective for the repair of stucco at this level of drift.

6.2.3 Gypsum Wallboard Damage Comparison

The damage sustained by the gypsum wallboard at the Stage 1 damage state is concentrated at the wall opening corners. The level of damage is very small and all repairs are simply an aesthetic consideration. Minor cracking of the finish and wallboard was repaired and compared at equivalent levels of drift. Figure 6.10 shows the general wallboard performance at a drift of 0.2%. The visual performance of the wallboard finish was nearly identical with small local variation. Figure 6.11 shows a location where the wallboard was simply painted to mask the damage and it can be seen that the damage for the repaired wall was nearly identical and the damage was first noticed at the same drift level.

Figure 6.12 shows a location where the wallboard crack was routed out and finished with setting-type joint compound. The first cracks formed at a smaller displacement level for the repaired corner, initiating at the edges of the routed crack, but the damage is still minimal. The fiberglass tape repair reduced the visual damage at this displacement level and can be seen in Figure 6.13. The slight bulging observed at the corner bead was effectively reduced with the use of repair tape. Figure 6.14 shows a location where paper tape was used. Again, the same level of damage was observed to occur at the same drift levels. For the fastener popping, the reset nails with the additional fastener installed at 1 in. away proved to be effective since the fastener popping was reduced at the previously repaired locations. All the repair methods used proved to be effective for repairing the interior wallboard finish of a structure that has experienced the Stage 1 level of damage.

6.3 Performance at 0.4% Drift: Stage 2 Repairs

6.3.1 Measured Performance Comparison

The repairs used at the Stage 2 damage state were similar to the repairs used at the Stage 1 damage state. The only significant change was the addition of supplemental
fasteners to the wall perimeter on both finish surfaces. Figure 6.15 shows the backbone curves for the walls before and after the Stage 2 damage repairs. It can be seen that the walls perform very well after the repairs were implemented, and the trailing cycles are shown to see the gain in structural performance if the walls were not repaired. The structural performance of the repaired walls is nearly identical to the original walls displaced up to 0.4% drift. Virtually no loss of stiffness or resistance was observed. The exceptional performance of the repaired walls was due to the increased wallboard rigidity from the large number of supplemental fasteners added at the Stage 2 damage state. The screws added at the sill plate level in the stucco contributed more at larger displacements.

The wall residual drifts can be seen in Figure 6.16, and for most cases the wall configurations that had the door opening sustained larger residual drifts as expected. The wall residual drifts also were observed to increase from the Stage 1 damage state drift, which was also expected. Similar to the recorded residual drifts at the Stage 1 damage state drift, the average residual drift is roughly 50% of the imposed drift. The residual drift for the repaired wall with the door configuration was reduced by 50% at the same level of drift, but the wall configuration having only windows exhibited the same magnitude of residual drift for all wall tests at 0.4% drift.

Figure 6.18 shows the recorded anchor uplift forces recorded for the anchor bolts located closest to the ends of the wall specimens. For the positive displacement cycles (the primary direction), the wall anchorage forces increased from the unrepaired specimens (b vs. c.b), yet the forces for the negative displacement cycles were reduced. This was caused by the increase in the effective lateral force transfer to the sill plate from the addition of supplemental screws at the sill plate level. For the negative displacement cycles, the force transfer mechanism was damaged during the primary loading direction due to the increase in the force demand, thus not allowing the equivalent force to be developed for the reverse cycles. From Figure 6.17 it can be seen that the repaired walls at the same level of drift dissipated less energy than the unrepaired walls at 0.4% drift. The difference of the amount of energy dissipated after the repairs is not of significant concern and the restored wall stiffness and resistance after the repairs outweigh the disadvantages. The repair methods used at the Stage 2 damage state were very effective.
in restoring the original resistance in the positive displacement direction and less than a 5% reduction in the negative displacement direction.

### 6.3.2 Portland Cement Plaster Damage Comparison

For the stucco finish at the Stage 2 damage state, a repair method specified by California Plastering Consultants was used. This method was nearly identical to method 3 used at the Stage 1 damage state. The most notable differences were the addition of an additional cementitious coating in which the fiberglass tape was embedded, and the addition of an acrylic bonding agent into the stucco finish coat. Figure 6.19 shows the general stucco crack patterns observed before and after the walls were repaired. The global damage pattern is nearly the same with some slight local variation. Figure 6.20 shows the average measured stucco crack widths at the Stage 2 damage drift, and the average crack widths were reduced. The addition of 2-1/2 in. deck screws to the stucco finish perimeter at the sill plate level caused cracking at the repair screw locations, but at this damage level these cracks were evaluated to be easily repaired.

Figure 6.21 to Figure 6.23 show the observed damage that occurred at various locations where a repair was performed. The stucco crack widths were reduced at most locations, but the crack lengths were not greatly affected. The cracks formed along the lengths of the original cracks at most locations. The measured crack widths were in the expected range when compared with the measured crack widths for Walls 1 and 2.

Aesthetically, the repair methods used for this damage level are recommended. The addition of the 2-1/2 in. screws also was observed to be effective in reducing the relative stucco panel movement with respect to the structural framing, although some cracking was observed at the repair screw locations.

### 6.3.3 Gypsum Wallboard Damage Comparison

At the Stage 2 damage state drift level, the gypsum wallboard damage is visually more obvious than the damage that was observed at the Stage 1 damage drift level. The repair methods used at the wall opening corners were the same because the observed magnitude of damage did not merit the use of more extreme repair methods. The addition of the supplemental screw fasteners for the Stage 2 damage state repairs was the main difference between the Stage 1 and Stage 2 damage state repair methods. The supplemental fasteners attached the wallboard to the structural framing more securely.
than with cooler nails alone. This was evident by the reduction of fastener popping observed. Since the wallboard was held more securely to the framing, the damage at opening corners and at the wallboard joints increased when compared to the walls at 0.4% drift, before the addition of supplemental screw fasteners.

The damage pattern is shown in Figure 6.24, and an increase in damage was observed at the wallboard joints and opening corners, yet the crack lengths and not the widths were observed to increase in magnitude. Figure 6.25 is a location where the wallboard cracks were routed and finished with setting-type joint compound. The cracks formed at the same displacement level, and the damage was nearly identical to what was observed before the repair. Figure 6.26 shows a location where fiberglass tape was used and the previously observed damage was essentially repeated, but the crack propagated further than previously observed, and the finish over the fiberglass tape flaked and bulged in compression. Figure 6.27 shows the damage that occurred to a location that had the crack and corner bead at the opening corner repaired using fiberglass tape. The corner bead cracking was eliminated, but the fiberglass tape had the finish flake off or crumble. Figure 6.28 shows a location where paper repair tape was used. The local behavior was nearly the same except the crack propagated further than previously observed and a slight bulge was noticed in the paper tape. Figure 6.29 shows the typical wallboard joint damage sustained after the damaged joint tape was stripped and replaced with fiberglass tape. The damage at each level was comparable, but the joint was first damaged at a displacement of 0.2% drift rather than 0.3% drift. The fiberglass tape and the addition of wallboard screws along the corner bead eliminated the corner bead cracks compared to same locations prior to the repair.

Overall, the wallboard repairs performed well. The change in wallboard stiffness from the additional screw fasteners had the most significant effect on the wall performance as similar damage sustained by the wall system occurred at smaller displacements, although the damage at 0.4% drift is comparable for both cases. All damage was evaluated to be easily repairable.
6.4 Performance at 0.7% Drift: Stage 3 Repairs

6.4.1 Measured Performance Comparison

The extent of repairs necessary after the Stage 3 damage state level of drift was significantly greater than the extent of repairs at the Stage 2 damage state level of drift. The amount of necessary repairs was an indicator of the increased structural damage to the walls. Figure 6.30 shows that the Stage 3 damage state repairs did not have an effect on the resistance for small displacement cycles, indicated by the similarity between the curves for the trailing cycles and the repaired walls. The repairs do increase the resistance and stiffness of the walls as the displacements became larger than the Stage 2 damage state drift of 0.4%. The resistance of the original walls was effectively restored using the Stage 3 damage state repairs with less than a 10%-15% reduction. Figure 6.31 shows the residual drifts measured after the imposed displacement of 0.7% drift and the average residual drift was roughly 45% of the maximum imposed drift.

The anchorage uplift forces recorded for the primary cycle of 0.7% displacement damaged the lateral force transfer mechanism enough that for the reverse cycle the wall anchors did not develop the same force that was achieved at the first primary displacement of 0.7% drift, which is shown in Figure 6.35. The damage to the attachment of the stucco and wallboard to the sill plate was sufficiently damaged to inhibit proper force transfer. The magnitude of stucco crack widths was similar as previously measured at equivalent drift levels, which is shown in Figure 6.32. The amount of energy dissipated by the walls is related to the equivalent viscous damping, which is shown in Figure 6.33. The amount of energy dissipated by the walls after the walls were repaired was less than before the walls were repaired, which is not necessarily desirable, but the overall performance of the walls after the Stage 3 damage state repairs validate the repair methods used, and the walls can be sufficiently repaired if these methods are used.

6.4.2 Portland Cement Plaster Damage Comparison

At the Stage 3 damage state level of drift, the stucco was observed visually degraded more rapidly compared to the Stage 2 damage state, and magnitude of damage significantly increased from the Stage 2 damage state. The crack pattern observed was similar to the unrepaired walls at the same drift level and can be seen in Figure 6.34.
local crack patterns varied slightly dependant on the repair. At the wall perimeter where the repair screws were installed, severe cracking was observed to run along the length of the sill plate for Wall 4, but the previously observed stucco panel movement relative to the structural framing was effectively inhibited, which was obvious since the corner stud twisting was reduced.

At some locations bulging was observed at the compression corners as the fiberglass tape, finish coat, and dry bond began to separate from the stucco brown coat. This effect was more severe at larger displacement levels. Figure 6.36 shows an open crack after 0.7% drift and the two relative magnitude of cracking was essentially the same. The only variation was that the repaired walls had more distributed cracks at the opening corners than previously observed. Since the repair areas were large for the Stage 3 damage level, the fiberglass tape, finish coat, and dry bond was spread out over a larger area. This larger area bulged and cracked more easily when the walls displaced.

Figure 6.37 and Figure 6.38 show near identical behavior at various opening corners and the separation of the repair tape and finish can also be observed as the finish coat bulged and flaked off of the repair tape. Depending on the quality of the repair application, the fiberglass tape bulged and/or separated from the stucco brown coat at some locations. At other locations, sufficient bond was achieved and the fiberglass tape ripped along the length of the crack, rather than bulged. At locations where the ripping of fiberglass tape was observed, the actual crack width was more clearly reflected than for the locations where compression bulging was observed.

### 6.4.3 Gypsum Wallboard Damage Comparison

At the Stage 3 damage state level of drift, the wallboard damage for the repaired walls and the original walls before the Stage 3 damage state repairs were used was the same. The only exception was at the locations where the wallboard sections experiencing excessive cracking and were removed and replaced. Figure 6.39 shows the general wallboard damage that occurred before and after the Stage 3 damage repairs. The main difference observed was the tendency of the fiberglass tape repairs to flake in some locations. At the locations where the wallboard was replaced, the damage was concentrated in the joints of the new wallboard and the crack widths at the opening corners were significantly reduced. At the locations where a horizontal wallboard joint
was adjacent to the location where removal and replacement of a wallboard section was warranted, the damage was again concentrated in the wallboard joint rather than at the opening corner.

Figure 6.40 shows a location where paper tape was used as the repair at the Stage 2 damage level and was loaded up to the Stage 3 damage level. Fiberglass repair tape was used for the Stage 3 damage repair. The paper tape bulged and cracked along the edges of the tape, and the finish flaked over the fiberglass tape. In Figure 6.41 the joint damage can be seen adjacent to where the wallboard section was removed and replaced, and the tendency of the fiberglass repair tape to flake is shown. Figure 6.42 is another location where paper tape was used as the Stage 2 damage repair and a similar bulging effect was observed. The Stage 3 damage repair at the same location involved the removal and replacement of the damaged section of the wallboard. It can be seen that the damage at the opening corner is reduced and the damage was concentrated in the new wallboard panel joints, and the main horizontal wallboard joint. The repaired corner bead shown in Figure 6.43 was observed to sustain a similar magnitude of damage, and the fiberglass tape again caused some flaking of the finish.

6.5 Failure

After Walls 3 and 4 were loaded to failure, the results of the two separate sets of tests (repaired Walls 3 and 4 versus Walls 1 and 2) were compared. The observed damage to the stucco and the wallboard finishes closely followed the same patterns with slight local variation caused by the various repairs used. Figure 6.44 and Figure 6.45 show the damage that each set of wall specimens sustained at failure. The global crack patterns were very similar with no significant change in behavior of the wall system. One of the main differences observed in the stucco behavior was the stucco panel movement relative to the structural framing was nearly eliminated for the repaired wall specimens. This also effectively reduced the observed corner stud twisting. The corner stud twisting of an actual building will also rely on the out-of-plane resistance of perpendicular walls, but this was difficult to model in the test setup. For Wall 4, the reduced stucco panel movement allowed for an extremely large crack to form after the capacity of the wall specimen was reached, whereas the stucco panels only separated from the framing after large displacements for the unrepaired case. After the capacity of the walls were reached,
the buckling of the wallboard sections observed for Wall 2 was eliminated by the addition of the supplemental fasteners. Again, the elimination of this damage caused very large cracks at the opening corner, which propagated up to the wallboard boundary.

The repaired walls were actually stronger than the un repaired walls with respect to the ultimate strength of Walls 1 and 2 and can be seen in Figure 6.46. This is not unexpected since the addition of the repair screws at the sill plate level significantly reduced and observed movement of the stucco relative to the framing. As a result, the overturning resistance was increased and was reflected in the anchorage uplift forces at equivalent drift levels. The tests have shown that if a wall has sustained damage consistent with the walls having developed forces up to 90% of the ultimate strength of the wall, that the original wall resistance and ultimate strength can be effectively restored using the prescribed methods at each damage state.

Figure 6.47 shows the comparison of the anchorage uplift forces of the two separate wall tests. The addition of supplemental fasteners at the sill plate level for both the exterior and interior wall finishes effectively achieved better force transfer as indicated by the higher anchorage forces developed. The primary direction of displacement significantly damaged the lateral force transfer mechanism to the sill plate evident by the forces developed during the reverse displacement cycle being less than 50% of the forces developed for the primary direction of displacement.

6.6 Repair Cost

The economic loss of structures plays a large role when making performance based engineering decisions. It is not uncommon that a structure, which did not sustain a significant amount of structural damage, was effectively a total loss due to the fact that the cost of repairing the aesthetic damage was determined to be greater than the value of the structure. Many factors affect the cost estimation for various repairs and the estimated cost can greatly vary between contractors. Factors that affect the total cost may include, geographic location of the structure, the ability to match the existing paint and texturing design, personal taste and accept ance levels, availability of materials, and the size of the structure and repair job.

In order to assign a relative cost to each damage state, a local contractor was consulted to evaluate and repair all finish damage after stages 1-3. Based on the cost of
the purchased materials, the number of man-hours needed to perform all repairs, and a percentage for the contractors mark-up, a cost of each repair was calculated for each damage state. The repair costs were correlated with the maximum story drift associated at each damage state level of drift. An increase in cost with the increase in drift is observed and can be seen in Figure 6.48. A summary of the repair costs specific to Phase I of the CEA/CUREE Woodframe Wall Testing Project is shown in Table 6.1 and is broken down to estimate the repair cost of the gypsum wallboard finish and the stucco finish.

The material cost was insignificant when compared to the cost of labor which was the dominating factor contributing to the rise in the total repair cost. Methods for determining cost estimations for each damage state were beyond the scope of the project and the repair cost data presented is intended to show the trend of increase in repair cost versus the increase in the drift levels measured. Chapter 7 covers the derived method for reasonably approximating the amount of structural damage sustained by a wall section by relating the average residual crack widths and residual drifts to a probable maximum imposed drift.
Table 6.1  Summary of Repair Cost

<table>
<thead>
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<sup>a</sup> Including 30% markup.
Figure 6.1 Global Wall Response at Stage 1 Damage State
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(c) Wall 3b.a  (d) Wall 4b.a

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Figure 6.37 Stucco Repair Method 1: Comparison for Wall 4c and Wall 4d.c
Figure 6.38  Stucco Repair Method 1: Comparison for Wall 4c and Wall 4d.c

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Chapter 7 Damage State Correlation

7.1 Introduction

The residual stucco crack widths and the residual story drift of an existing structure after an earthquake can be obtained by measurement. The residual story drift is a measure of the permanent deformation of the double top plate relative to the bottom sill plate and can be reasonably estimated with a carpenter level at doorjambs or other convenient locations. By relating the residual stucco crack widths and the residual story drift to a maximum imposed story drift that the walls sustained, it is possible to determine the amount of damage sustained to the wall. Based on ranges of values, it is possible to estimate the relative magnitude of the developed forces and the relative magnitude of damage that was sustained by the structure.

The quantitative methods presented below must be used in concert with qualitative assessment of cracking patterns and comparison of observed cracking patterns with those presented in Chapters 4, 5, and 6 to accurately assess the condition of a wall.

7.2 Development

Collected data was used for correlation between the measured and recorded response of the walls. The residual crack widths, the residual drift, and the maximum imposed drift were used for observable trends. The residual crack widths measured after each displacement cycle represent an upper bound of residual crack widths that would be measured if a wall were subjected to the measured maximum imposed drift (see the least squares fit marked as “Displaced Walls” in Figure 7.1). Because of the random nature of earthquake ground motions, two structures that have experienced the exact same maximum imposed displacements due to different earthquake ground motions could have different measured residual drifts and residual crack widths. For this reason, the residual crack widths of Walls 3 and 4 were also measured after 0.4% and 0.7% drift with the walls returned to a plumb position. These crack widths represent the lower bound of cracking that would be measured if the structure came to equilibrium in a plumb position.

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5 This analysis assumes that earthquake induced wall distortion is the sole source of cracking in the stucco. The effects of stucco shrinkage and differential structural movement will increase the observed crack widths in actual structures.
(see the least squares fit marked as “Plumb Walls” in Figure 7.1). This gives a range of crack widths that are expected for a given imposed story drift that can be related to the maximum story drift. The upper bound on story drift (based on residual crack widths measured in the plumb position) was reduced by 35% to produce a conservative average residual crack width that could be related to each damage state level of drift; the relationship marked as “Recommended” in Figure 7.1 can be expressed as follows:

\[ \Delta_m = 25.47C_w + 0.114 \]  

(7.1)

where \( \Delta_m \) is the story drift (in in.), and \( C_w \) is the residual crack width (in in.).

Once an estimated story drift for a measured residual crack width is established, the story drift can be related to the strength ratio. The strength ratio, \( SR \), was defined earlier in this report as the maximum force developed at a given displacement divided by the measured capacity of the test specimen. The fitted curve and corresponding data points are shown in Figure 7.2. The relationship between the two variables was determined using a least squares fit (Weisberg, 1985):

\[ \Delta_m = 0.83(SR)^{1.77} \]  

(7.2)

The relationship between residual drift (\( \Delta_r \), in in.) and story drift is (see Figure 7.3):

\[ \Delta_m = 2.70\Delta_r + 0.0553 \]  

(7.3)

and the relationship between residual drift and residual crack width is (see Figure 7.4):

\[ C_w = 0.098\Delta_r + 0.0012 \]  

(7.4)

For all wall specimens tested, the residual crack widths and the residual drifts were plotted versus the calculated secant stiffness. The secant stiffness was calculated by taking the maximum force developed for a given displacement cycle and dividing it by the imposed drift at that level of force (see Figure 7.5). The relationships of the crack width and the residual drift on the secant stiffness (\( k_{sec} \), in kip/in.) is shown in Figure 7.6 and Figure 7.7:

\[ k_{sec} = 6.678(C_w)^{-0.344} \]  

(7.5)
\[
 k_{\text{sec}} = 11.082\Delta_r^{-0.445}
\]  

(7.6)

### 7.3 Practical Application

After the inspection of the exterior walls of a structure, the walls can be effectively placed into one of four categories determined from the derived graphs. The defined limits of each damage state are to be used as a guide and are not intended to represent absolute limits. The following method, along with experience and engineering judgment, must be used to properly categorize damage. Different walls of a structure may be placed into different categories because the level of damage sustained will vary depending on the geometry of the structure or the presence of any structural irregularities such as torsion, soft-story conditions, or large diaphragm openings. Again, engineering judgment must be used to classify the structure as a whole.

The average residual crack widths for each Stage of drift were determined from the recommended curve established in Figure 7.1. The recommended average residual crack widths at Stages 1, 2, and 3 damage states are 0.004 in., 0.012 in., and 0.023 in., respectively. The limits shown for each damage state designated by the vertical dashed lines in Figure 7.8 represent practical limits for the average crack widths for each damage state. These limits represent the average residual crack width that were measured (at zero wall force) for the case of maximum residual drift after an imposed drift of 0.2% and 0.7% and is represented by the lower dashed line. The limit for Stage 2 damage was determined from a linear interpolation between the lower dashed line at Stage 2 drift of 0.4% and the upper dotted line for Stage 3.

Once an average crack width is calculated from the measured primary cracks at all opening corners of a wall, the approximate level of maximum story drift can be determined from the recommended curve (solid line, or Eq. 7.1) in Figure 7.8. Once the maximum story drift is attained, an estimation of the expected residual drift of the wall can be found from the curve in Figure 7.9 (or Eq. 7.3) and checked versus a measured residual drift of the wall. Figure 7.10 is a fitted curve for the actual measured relationship from testing and can be used as a guide for deciding if the story drift attained from Figure 7.8 is reasonable. The solid line is the fitted curve of the experimental data,
the dashed/dotted line is the residual drift determined from Figure 7.8 and Figure 7.9 from the recommended curve. The lower dotted line is the residual drift determined from the limit of the plumb walls and the upper dashed line is the residual drift determined from the displaced walls in Figure 7.8.

From Figure 7.10 it can be seen that the recommended curve established in Figure 7.8 yields reasonable results with respect to the fitted curve of the measured data. If the measured average residual crack widths and measured residual drift falls reasonably within the range, the approximate strength ratio can be estimated from Figure 7.11. For measured average residual crack widths that fall into the Stage 1 damage state range, a larger variation of the measured crack widths and residual drifts is expected due to the observed variation seen in Figure 7.4, but the variation decreases with an increase in imposed drift. Because of this, engineering judgment must be used when deciding upon the classification between Stage 1 and Stage 2 damage for borderline measurements. Other means of structural evaluation may be necessary for making a proper classification.

Figure 7.12 shows the relationship between the calculated secant stiffness versus the measured crack width and the corresponding recommended damage state limits are represented by the vertical dashed lines. An outlined procedure for classifying the approximate damage sustained to walls of similar construction as those tested in this project is described in Figure 7.13.

From the global structural response, the relative magnitude of damage, and the relationships between selected measured data, the conclusions drawn for determining damage state drift levels and repair efficacy is presented in Chapter 8.
Figure 7.1  Linear Approximation of Crack Width ($C_w$) versus Story Drift ($\Delta_m$)

\[ \Delta_m = 25.47(C_w) + 0.114 \]

Figure 7.2  Strength Ratio ($SR$) versus Story Drift ($\Delta_m$)

\[ \Delta_m = 0.83(SR)^{1.77} \]
Figure 7.3 Residual Drift ($\Delta_r$) versus Story Drift ($\Delta_m$)

$\Delta_m = 2.70\Delta_r + 0.0553$

Figure 7.4 Residual Drift ($\Delta_r$) versus Crack Width ($C_w$)

$C_w = 0.098\Delta_r + 0.0012$
Figure 7.5  Secant Stiffness Definition

Figure 7.6  Avg. Residual Crack Width ($C_w$) versus Secant Stiffness ($k_{sec}$)

$$k_{sec} = 6.678(C_w)^{-0.344}$$
Figure 7.7 Secant Stiffness versus ($k_{sec}$) Residual Drift ($\Delta_r$)

\[ k_{sec} = 11.082(\Delta_r)^{-0.445} \]

Figure 7.8 Crack Width ($C_w$) versus Story Drift ($\Delta_m$)
Figure 7.9 Residual Drift ($\Delta_r$) versus Story Drift ($\Delta_m$)

Figure 7.10 Residual Drift ($\Delta_r$) versus Crack Width ($C_w$)
Figure 7.11 Strength Ratio ($SR$) versus Story Drift ($\Delta_m$)

Figure 7.12 Crack Width ($C_w$) versus Secant Stiffness ($k_{sec}$)
Step 1
Measure all primary crack widths at wall opening corners along a wall section and compute the average. Approximate the residual drift. Determine approximate story drift from the graph.

Step 2
Use the determined story drift to approximate an expected level of residual drift.

Step 3
Check the measured average crack width and the measured residual drift versus expected values from the graph. Use engineering judgment to determine correct approximation of story drift.

Step 4
Use the determined story drift to approximate the level of force resisted by the wall with respect to the wall capacity. Evaluate secant stiffness to determine structural damage sustained by the wall.

Figure 7.13 Procedure for Classifying Wall Damage
Chapter 8  Summary and Conclusions

8.1  Summary

Four 8 ft by 16 ft wall specimens representative of conventional 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 Figure 3.7 to Figure 3.9 for construction details).

The first set of wall specimens was cyclically loaded to failure. These walls served as the reference walls for the subsequent testing specimens. 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 5. The second set of wall specimens were tested and repaired at each Stage (no repairs made following Stage 4 loading). Various repair methods were used at each Stage for both the exterior stucco finish and the interior gypsum wallboard finish. Table 5.1 shows the repair methods used for repairing the stucco at Stage 1 and Table 5.3 shows the stucco repair methods used at Stages 2 and 3. Table 5.2, Table 5.4, and Table 6.1 shows the gypsum wallboard repair methods used at the Stage 1, Stage 2, and Stage 3, respectively.

At each Stage, 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 conclusions drawn are as follows.

8.2  Conclusions

8.2.1  Structural Response

1) The wall test specimens exhibited ultimate strengths of 15 kips at 1 to 1.5% of drift. While the drift at ultimate strength was consistent with prior studies, the strength per net wall length was much greater than shown in prior tests of solid wall panels, or permitted by current codes.

2) 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.

(3) At drift levels below 0.7% little or no deterioration (either structural or cosmetic) was observed during trailing cycles.

(4) For the walls repaired at the Stage 1 damage level, some unrecoverable initial stiffness loss was observed upon reloading, but the original stiffness and resistance of the walls was nearly restored. Walls that have experienced drifts levels near 0.2% can be effectively repaired using the previously mentioned methods with a secant stiffness reduction of less than 5%.

(5) For the walls repaired at the Stage 2 damage level, the repair methods used were very effective in restoring stiffness of the damaged walls at an equivalent level of drift. Walls that have experienced drift levels near 0.4% can be repaired with the previously mentioned methods with less than a 5% reduction of secant stiffness.

(6) Using the repair methods specified for Stage 3 damage, the stiffness of the walls can be recovered with a secant stiffness reduction of less than 15% at this level of drift.

(7) The ultimate strength and stiffness of the repaired walls was greater in the primary loading direction than the reference walls with an increase in ductility and less than a 5% reduction of the ultimate capacity in the secondary loading direction.

(8) The stiffness and ultimate strength of the walls are largely controlled by the attachment of the finishes to the framing. The addition of supplemental fasteners can effectively restore both the stiffness and ultimate strength of walls subjected to less than 0.7% drift.

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

(10) Existing stucco cracks caused by one level of displacement did not increase in magnitude when subjected to smaller displacement cycles.
Stucco cracks which occurred at small drift levels did not affect the wall resistance at larger drift levels.

8.2.2 Portland Cement Plaster

The condition of the stucco finish can be related to story drift by comparing the measured stucco crack widths and correlating them with the structural response at various levels of imposed drift. With proper engineering judgment, the procedure outlined in Chapter 7 can accurately classify earthquake damage. Recommended values for average residual crack widths are presented.

(1) Wall specimens experiencing roughly 0.2% drift had average stucco crack widths of near 0.004 in. and few greater than 0.01 in. Recommended limit is 0.0085 in. Damage is limited to small cracks originating at opening corners.

(2) Wall specimens experiencing roughly 0.4% drift had average stucco residual crack widths of roughly 0.012 in. and few greater than 0.025 in. Recommended limit is 0.0189 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 0.023 in. and few greater than 0.05 in. Recommended limit is 0.0281 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: Painting over hairline cracks (<0.002 in.) was effective in masking this level of crack widths. The stucco cracks reopened along the original lengths and did not significantly increase in length or width. Routing the crack along the length and dusting the crack with stucco patch reduced the crack widths
upon reloading at the same drift level and the cracking pattern observed was nearly identical. This repair was shown to be effective for stucco cracking less than or equal to 0.005 in. 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 stucco cracking less than or equal to 0.009 in. Both the crack width and lengths were reduced upon reloading.

(2) Stage 2 Repair: The repair specified by California Plastering Consultants was effective in reducing the stucco crack widths at most locations for measured crack widths of 0.04 in. or less. The addition of deck screws at the sill plate perimeter nearly eliminated any observed stucco movement relative to the structural framing.

(3) Stage 3 Repair: The repair method was effective in limiting the stucco cracking to the same magnitude of crack widths at all locations. The addition of supplemental fasteners at the sill plate level along the perimeter of the walls for the Stage 2 damage state attracted stucco cracking at many fastener locations, but the stucco movement with respect to the structural framing was significantly reduced compared to the reference walls at the same drift level.

(4) Building paper tearing occurred at drift levels near ultimate strength.

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.

(2) At the Stage 2 drift level of 0.4%, the gypsum wallboard panels began to visually deteriorate and cracking at the opening corners of 0.005 in. to 0.025 in. was common with an average near 0.017 in. Wallboard joints began to 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.

(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 0.002 in. to 0.05 in. with an average on near 0.03 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 most 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: Painting over the hairline cracks proved to be an effective cover up and the cracks occurred at the same displacement levels as previously observed. Routing the cracks along their length and finishing with setting-type joint compound was also found to be effective for reducing wallboard crack widths of 0.005 in. or less. The fiberglass tape and the paper tape repairs effectively repeated the original performance of the wallboard up to 0.2% drift. Both methods of repairing fastener popping were effective in retarding the development of future fastener popping at those locations only.

(2) Stage 2 Damage: Routing out the cracks and finishing with a setting-type joint compound was effective for reducing the crack widths for cracks of 0.025 in. or less, but the lengths were observed to slightly increase at these locations. Small hairline cracks formed at smaller displacement levels than previously observed. The use of paper tape was effective in reducing wallboard crack widths at all locations for cracks of 0.025 in. or less. The fiberglass tape was effective in reducing the crack widths at most locations for similar crack widths, but the wallboard finish was observed to flake off and buckle in compression at these locations. The addition of supplemental screw fasteners at various wallboard locations was very effective in reducing the fastener popping as it was nearly eliminated at this drift level.
Stage 3 Repairs: 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 completely eliminated the total separation of the wallboard from the structural framing.

8.2.4 Damage Assessment

When residual stucco crack widths and residual story drift of a structure can be readily measured after an earthquake, an estimation of the amount of structural damage sustained by the wall may be determined. By relating the residual stucco crack widths and the residual story drift to a maximum imposed story drift, it is possible to determine the relative magnitude of the developed forces for structures of similar construction. The methodology used for the development of a procedure to reasonably determine structural damage of walls after a seismic event is covered in Chapter 7.

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 the deficiencies of the current lateral design of 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 that 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 design of a structure could lead to a grossly over-designed structure. This may seem like a reasonable short-term solution to the current design problems, but in reality it can be very dangerous. Using the principles of capacity design, neglecting the effects of certain structural elements of a building to the overall performance can be disastrous. The actual force demand on certain structural components of a shear wall 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, the results could be fatal, which is contrary to structural engineering philosophy.

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.
References


