Seismic Performance of Gypsum Walls: Experimental Test Program

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Preface

The CUREE-Caltech Woodframe Project originated in the need for a combined research and implementation project to improve the seismic performance of woodframe buildings, a need which was brought to light by the January 17, 1994 Northridge, California Earthquake in the Los Angeles metropolitan region. Damage to woodframe construction predominated in all three basic categories of earthquake loss in that disaster:

- **Casualties:** 24 of the 25 fatalities in the Northridge Earthquake that were caused by building damage occurred in woodframe buildings (1);
- **Property Loss:** Half or more of the $40 billion in property damage was due to damage to woodframe construction (2);
- **Functionality:** 48,000 housing units, almost all of them in woodframe buildings, were rendered uninhabitable by the earthquake (3).

Woodframe construction represents one of society’s largest investments in the built environment, and the common woodframe house is usually an individual’s largest single asset. In California, 99% of all residences are of woodframe construction, and even considering occupancies other than residential, such as commercial and industrial uses, 96% of all buildings in Los Angeles County are built of wood. In other regions of the country, woodframe construction is still extremely prevalent, constituting, for example, 89% of all buildings in Memphis, Tennessee and 87% in Wichita, Kansas, with "the general range of the fraction of wood structures to total structures...between 80% and 90% in all regions of the US….” (4).

Funding for the Woodframe Project is provided primarily by the Federal Emergency Management Agency (FEMA) under the Stafford Act (Public Law 93-288). The federal funding comes to the project through a California Governor’s Office of Emergency Services (OES) Hazard Mitigation Grant Program award to the California Institute of Technology (Caltech). The Project Manager is Professor John Hall of Caltech. The Consortium of Universities for Research in Earthquake Engineering (CUREE), as subcontractor to Caltech, with Robert Reitherman as Project Director, manages the subcontracted work to various universities, along with the work of consulting engineers, government agencies, trade groups, and others. CUREE is a non-profit corporation devoted to the advancement of earthquake engineering research, education, and implementation. Cost-sharing contributions to the Project come from a large number of practicing engineers, universities, companies, local and state agencies, and others.

The project has five main Elements, which together with a management element are designed to make the engineering of woodframe buildings more scientific and their construction technology more efficient. The project’s Elements and their managers are:

1. **Testing and Analysis:** Prof. André Filiatrault, University of California, San Diego, Manager; Prof. Frieder Seible and Prof. Chia-Ming Uang, Assistant Managers
2. **Field Investigations:** Prof. G. G. Schierle, University of Southern California, Manager
3. **Building Codes and Standards:** Kelly Cobeen, GFDS Engineers, Manager; John Coil and James Russell, Assistant Managers
4. **Economic Aspects:** Tom Tobin, Tobin Associates, Manager
5. **Education and Outreach:** Jill Andrews, Southern California Earthquake Center, Manager
The Testing and Analysis Element of the CUREE-Caltech Woodframe Project consists of 23 different investigations carried out by 16 different organizations (13 universities, three consulting engineering firms). This tabulation includes an independent but closely coordinated project conducted at the University of British Columbia under separate funding than that which the Federal Emergency Management Agency (FEMA) has provided to the Woodframe Project. Approximately half the total $6.9 million budget of the CUREE-Caltech Woodframe Project is devoted to its Testing and Analysis tasks, which is the primary source of new knowledge developed in the Project.

### Woodframe Project Testing and Analysis Investigations

<table>
<thead>
<tr>
<th>Task #</th>
<th>Investigator</th>
<th>Topic</th>
</tr>
</thead>
</table>
| 1.1.1  | André Filiatrault, UC San Diego  
Kelly Cobeen, GFDS Engineers | Two-Story House (testing, analysis)  
Two-Story House (design) |
| 1.1.2  | Khalid Mosalam, Stephen Mahin, UC Berkeley  
Bret Lizundia, Rutherford & Chekene | Three-Story Apt. Building (testing, analysis)  
Three-Story Apt. Building (design) |
| 1.1.3  | Frank Lam et al., U. of British Columbia | Multiple Houses (independent project funded separately in Canada with liaison to CUREE-Caltech Project) |
| 1.2    | Bryan Folz, UC San Diego | International Benchmark (analysis contest) |
| 1.3.1  | Chia-Ming Uang, UC San Diego | Rate of Loading and Loading Protocol Effects |
| 1.3.2  | Helmut Krawinkler, Stanford University | Testing Protocol |
| 1.3.3  | James Beck, Caltech | Dynamic Characteristics |

#### Component-Level Investigations

| 1.4.1.1 | James Mahaney; Wiss, Janney, Elstner Assoc. | Anchorage (in-plane wall loads) |
| 1.4.1.2 | Yan Xiao, University of Southern California | Anchorage (hillside house diaphragm tie-back) |
| 1.4.2   | James Dolan, Virginia Polytechnic Institute | Diaphragms |
| 1.4.3   | Rob Chai, UC Davis | Cripple Walls |
| 1.4.4.4 | Gerard Pardoen, UC Irvine | Shearwalls |
| 1.4.6   | Kurt McMullin, San Jose State University | Wall Finish Materials (lab testing) |
| 1.4.6   | Gregory Deierlein, Stanford University | Wall Finish Materials (analysis) |
| 1.4.7   | Michael Symans, Washington State University | Energy-Dissipating Fluid Dampers |
| 1.4.8.1 | Fernando Fonseca, Brigham Young University | Nail and Screw Fastener Connections |
| 1.4.8.2 | Kenneth Fridley, Washington State University | Inter-Story Shear Transfer Connections |
| 1.4.8.3 | Gerard Pardoen, UC Irvine | Shearwall-Diaphragm Connections |

#### Analytical Investigations

| 1.5.1  | Bryan Folz, UC San Diego | Analysis Software Development |
| 1.5.2  | Helmut Krawinkler, Stanford University | Demand Aspects |
| 1.5.3  | David Rosowsky, Oregon State University | Reliability of Shearwalls |
Not shown in the tabulation is the essential task of managing this element of the Project to keep the numerous investigations on track and to integrate the results. The lead management role for the Testing and Analysis Element has been carried out by Professor André Filiatrault, along with Professor Chia-Ming Uang and Professor Frieder Seible, of the Department of Structural Engineering at the University of California at San Diego.

The type of construction that is the subject of the investigation reported in this document is typical “two-by-four” frame construction as developed and commonly built in the United States. (Outside the scope of this Project are the many kinds of construction in which there are one or more timber components, but which cannot be described as having a timber structural system, e.g., the roof of a typical concrete tilt-up building). In contrast to steel, masonry, and concrete construction, woodframe construction is much more commonly built under conventional (i.e., non-engineered) building code provisions. Also notable is the fact that even in the case of engineered wood buildings, structural engineering analysis and design procedures, as well as building code requirements, are more based on traditional practice and experience than on precise methods founded on a well-established engineering rationale. Dangerous damage to US woodframe construction has been rare, but there is still considerable room for improvement. To increase the effectiveness of earthquake-resistant design and construction with regard to woodframe construction, two primary aims of the Project are:

1. Make the design and analysis more scientific, i.e., more directly founded on experimentally and theoretically validated engineering methods and more precise in the resulting quantitative results.

2. Make the construction more efficient, i.e., reduce construction or other costs where possible, increasing seismic performance while respecting the practical aspects associated with this type of construction and its associated decentralized building construction industry.

The initial planning for the Testing and Analysis tasks evolved from a workshop that was primarily devoted to obtaining input from practitioners (engineers, building code officials, architects, builders) concerning questions to which they need answers if they are to implement practical ways of reducing earthquake losses in their work. (Frieder Seible, André Filiatrault, and Chia-Ming Uang, Proceedings of the Invitational Workshop on Seismic Testing, Analysis and Design of Woodframe Construction, CUREE Publication No. W-01, 1999.) As the Testing and Analysis tasks reported in this CUREE report series were undertaken, each was assigned a designated role in providing results that would support the development of improved codes and standards, engineering procedures, or construction practices, thus completing the circle back to practitioners. The other elements of the Project essential to that overall process are briefly described below.

To readers unfamiliar with structural engineering research based on laboratory work, the term “testing” may have a too narrow a connotation. Only in limited cases did investigations carried out in this Project “put to the test” a particular code provision or construction feature to see if it “passed the test.” That narrow usage of “testing” is more applicable to the certification of specific models and brands of products to declare their acceptability under a particular product standard. In this Project, more commonly the experimentation produced a range of results that are used to calibrate analytical models, so that relatively expensive laboratory research can be applicable to a wider array of conditions than the single example that was subjected to simulated earthquake loading. To a non-engineering bystander, a “failure” or “unacceptable damage” in a specimen is in fact an instance of successful experimentation if it provides a valid set of data that builds up the basis for quantitatively predicting how wood components and systems of a wide variety will perform under real earthquakes. Experimentation has also been conducted to improve the starting point for this kind of research: To better define what specific kinds of simulation in the laboratory best represent the real conditions of actual buildings subjected to earthquakes, and to develop protocols that ensure data are produced that serve the analytical needs of researchers and design engineers.
Notes


Acknowledgements

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U.S. Gypsum Corporation donated the FIBERROCK material for Test #13. The assistance of Dave MacDonald in determining and providing the appropriate material was greatly appreciated.

This report is one portion of the research conducted for Task 1.4.6. A companion study was conducted at Stanford University during the same period of time. Collaboration between the two projects was beneficial in the design of the test specimen and test matrix. The advice provided by Gregory Deierlein of Stanford University and John Osteraas of Exponent Failure Analysis Associates was greatly appreciated. In addition, review and comments from the Project Managers of the CUREE-Caltech Woodframe Project were collected and used to assist in the continual improvement of the research plan. The authors appreciate the assistance and guidance provided by Andre Filiatrault from the University of California at San Diego.

The specimens were built and tested in the laboratories of San Jose State University. The guidance of Dave Hemer, laboratory technician was of great assistance. Hugo Villabona, graduate research student, was responsible for the original construction of the testing frame and assistance in assembling the final report. Student researchers Loan-Anh Nguyen and Seri Ngerwattana were helpful in building, compounding and finishing the wall specimens. Tim Wann of Tim Wann Construction, Santa Cruz, CA provided construction guidance.
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Summary

Seventeen experimental tests were conducted to meet the required research objectives of determining the cost-damage relationship and engineering characteristics of residential gypsum wallboard partition walls. Specimens were 8-foot high and 16-foot long, double-sided with 1/2” gypsum wallboard. Test variables included: fastener type and spacing, loading protocol, top-of-wall boundary condition, method of attaching the wallboard to the top sill, wall opening layout, innovative construction methods, influence of door and floor trim, and repair strategies. Instrumentation measured applied load, lateral deflection at the top of the wall, lateral deflection at the bottom of the wall, shear distortion of the piers, and uplift at the door trimmers.

Findings include a distinct change in strength for walls built with various fastener types and wall penetration layouts. Damage patterns begin with the initiation of cracks at the wall penetrations and cracking of the paint over a few fastener heads, usually initiating at drift levels near 0.25%. Maximum loads are sustained at drifts of approximately 1 to 1.5%. At this point, one of two failure modes initiates. The first failure mode seen was loosening of the wallboard from the framing by pulling fastener heads through the back of the wallboard. The second failure mode included failure of the taped wall joints and racking movement of the individual wallboard panels. Strength degradation may be severe or more gradual for different walls. Monotonic loading protocols closely predict the cyclic force-displacement backbone relationship. The overall behavior and levels of damage appears to be related to the rigidity and geometry of the boundary elements of the wall. Rigid restraint from the intersecting walls appears to significantly increase the lateral strength and stiffness.

Cost-damage relationships appear to be similar to a step-function. The cost of repair seems closely related to the number of tradesmen required for repair work. While a single multi-skilled contractor can repair minor cracking, larger levels of damage may require demolition crews, drywall crews, carpenters and paint crews. Total loss of economic value of the wall appears to occur at drifts of approximately two percent.
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Chapter 1. Introduction

This report describes the experimental testing of gypsum wallboard partition walls for use in residential woodframe construction. Task 1.4.6 was one facet of the multi-task CUREE-Caltech Woodframe Project developing better understanding of woodframe residential structures, both single and multi-unit dwellings. The need for better understanding of the behavior of these structures was illustrated in the 1994 Northridge Earthquake, when significant economic loss was recorded for these types of structures. The extent of damage in the Northridge Earthquake may have been especially significant, but damage resulting in economic loss to residential structures is reported after nearly every significant earthquake.

Overall goals of Task 1.4.6 of the CUREE-Caltech Woodframe Project are to: (1) establish a prediction of the expected repair costs to common surface finishes, (2) define and quantify seismic performance levels for common residential wood-frame wall surface finishes, (3) establish engineering parameters and damage threshold deformations of wall systems, and (4) explore innovations to wall finishes that can improve their seismic performance. These goals were to gain understanding of the behavior of gypsum partition walls to allow for performance based engineering practice.

Task 1.4.6 was divided into two coordinated research projects. This report discusses the experimental test program conducted at San Jose State University. Analytical studies were conducted at Stanford University by Gregory Deierlein as a companion investigation in the Woodframe Project. The interested reader is referred to the Stanford study for supporting information.

Primary Objective

The scope of this project was for gypsum wallboard partition walls that might be commonly used in woodframe construction. Better understanding of new construction was the focus of the project, however it was believed that additional understanding of existing construction could also be obtained. The walls researched were standard construction according to the single family dwelling requirements of the, 1997 Uniform Building Code. Fire-rated walls and horizontal ceilings were beyond the scope of the study.

The primary objective of Task 1.4.6 was to determine a cost-damage relationship as a function of lateral drift. Damage thresholds were identified during the testing and the drift recorded when each specimen reached each threshold. At various levels of drift ratios (drift / height) [0.25, 0.50, 0.75, 1, 2 and 4%] the wall specimens were documented photographically to show the overall damage (number of nails or screws damaged and distribution across the wall) as well as the local damage (crack length, distribution, etc.). Four of these tests, representing more common construction styles, were evaluated for the cost of repair at the drift levels listed.
Secondary Objectives

In addition to the primary objective, Task 1.4.6 had several additional objectives. In addition to the primary research objective, the secondary objectives of the Task were:

1. Compare the performance of walls using screws versus nails to attach the wallboard and evaluate the effect of changing the spacing of fasteners.
2. Compare the behavior of the walls for monotonic versus cyclic loading protocols.
3. Compare walls built using floating edge construction (no fasteners within the top several inches of the wall) with walls built with fasteners at the top plate.
4. Compare walls where the top of the wall deforms laterally without vertical deflection to walls where vertical deflection is allowed.
5. Compare the influence of window openings on the behavior of the wall.
6. Compare the effect of building walls with butt-joints placed in the location of openings to walls where the butt-joints were located away from the opening.
7. Determine if simple alterations to the construction process result in improved engineering performance.
8. Evaluate the performance of walls that are damaged, repaired, and reloaded.

ASTM Standards for Partition Walls

The American Society of Testing and Manufacturing (ASTM) has several specifications outlining the testing of entire gypsum wall assemblies and components of those walls. The following is a brief list of some of the standards relevant to this project.

C11 Standard Terminology Relating to Gypsum and Related Building Materials and Systems
C22 Standard Specification for Gypsum
C36 Standard Specification for Gypsum Wallboard
C472 Standard Test Methods for Physical Testing of Gypsum, Gypsum Plasters and Gypsum Concrete
C474 Standard Test Methods for Joint Treatment Materials for Gypsum Board Construction
C475 Standard Specification for Joint Compound and Joint Tape for Finishing Gypsum Board
C514 Standard Specification for Nails for the Application of Gypsum Board
C557 Standard Specification for Adhesives for Fastening Gypsum Wallboard to Wood Framing
C840 Standard Specification for Application and Finishing of Gypsum Board
C954 Standard Specification for Steel Drill Screws for the Application of Gypsum Board or Metal Plaster Bases to Steel Studs From 0.033 in. (0.84 mm) to 0.112 in. (2.84 mm) in Thickness
C1002 Standard Specification for Steel Drill Screws for the Application of Gypsum Board or Metal Plaster Bases

Uniform Building Code Requirements for Partition Walls

In this portion of the report all references to tables, chapters and sections refer to the Uniform Building Code.

The Uniform Building Code (International Council of Building Officials, 1997) discusses gypsum board or plaster partition walls in Chapter 25. Additionally, Chapter 23 provides information and requirements for conventional light-frame construction.

Table 25-G lists maximum spacing of fasteners for partition walls. For vertical applications using 1/2-inch gypsum wallboard, the code requires nails to have a maximum spacing of 8 inches and screws to have a maximum spacing of 16 inches. Anecdotal information from industry reports that these allowable spacings are larger than is commonly used. In addition, if shear strength is expected from the wall assembly, the maximum spacing is reduced to the levels stated in Table 25-I. Since shearwall testing was performed by other researchers of the CUREE-Caltech Woodframe project, the spacing of fasteners for Task 1.4.6 were chosen to represent wall construction not designed to provide lateral resistance to the structure.

In Section 2511.3 the Code allows for floating edge construction of single-ply applications of wallboard. In the second paragraph it is stated that the fasteners to top and bottom plates may be omitted so long as the wall is not intended to provide shear resistance and/or be used as a fire-rated assembly.

In Section 2320.5.1 braced walls are required to be located within 25 feet of each other for conventional construction to be used in seismic zone 4, which includes most of California. Due to this requirement, interior walls may be required to be braced walls. In Section 2320.11.3 under Method 5 gypsum wallboard is only qualified as a braced wall when nails are used as the fastener. Likewise, the minimum panel length is limited to 48 inches for double-sided wall construction.
Chapter 2. Literature Review

The two most common wall finishes in woodframe structures are gypsum drywall and Portland cement plaster (stucco). This chapter summarizes common construction practices, available experimental data, and engineering design information for these two wall finishes. Included are results of a survey of practitioners in the Northern California region that help establish common practice for gypsum wallboard construction.

Test programs on gypsum wallboard from the engineering literature are reviewed and relevant tests and important behavior modes are noted. The test programs had varying objectives and correlation between tests was limited. However common behavioral patterns and properties are identified. Reported shear strengths of 8-foot high wall panels varied from 170 to 640 lb/foot, and secant stiffness, measured at the point of peak load, varied from 370 to 2300 lb/inch/foot. These shear strengths significantly exceed code specified strengths of 150 lb/foot. Initial damage was reported to occur at drift ratios on the order of 0.2 to 0.3%. Significant differences between monotonic and cyclic tests were observed in the sense that cyclic tests show lower values for strength and damage displacements and significant stiffness degradation. It was also observed that the type of connectors (screws versus nails) affect the damage behavior to a much larger extent than other factors such as the framing material or the wall thickness.

Introduction

Much of the available literature on wall finishes is based upon wall systems used as portions of the building’s lateral restraint system. Test results have been reviewed from university research projects, industry sources and private engineering firms.

Woodframe structures are built with a wide variety of architectural finishes on the walls. Modern structures usually rely upon plywood or wood product shearwalls such as OSB for lateral strength. Plywood is seldom the final surface of the wall and is usually covered with either drywall or a cementitious material, such as gypsum wallboard or Portland cement (stucco), for both the sake of appearance and fire resistance. Gypsum wallboard is also commonly used for architectural the non-structural partitions. To obtain insight into current building practices, a three-page questionnaire was mailed to 67 drywall contractors in the San Jose region, and a total of 19 questionnaires were returned and processed.

In the past, many buildings were built with the expectation that these cementious wall finishes would provide a significant amount of lateral strength and stability. Over the past thirty years the assumption that the gypsum wallboard can assist in resisting lateral force has been significantly reduced. The reduction in code strength values has generally developed in result to the significant damage occurring in light-frame structures in past earthquakes. The consensus has been that these buildings need support from shearwalls built from more robust materials, usually plywood or some other wood product.
A brief history has been compiled of the engineering of residential construction in California (Federal Emergency Management Agency, 1997, pp.8-1). In 1934 structures began to be designed for seismic lateral loads but single-family residential structures generally were not engineered. Platform construction using cripple walls was generally discontinued around 1950 and later seismic building code requirements for timber buildings began to be widely enforced. After 1970 structures generally were designed with a well-defined lateral-force resisting system, although construction quality and code enforcement varies widely.

**Gypsum Wallboard Construction**

The most common interior wall finish for modern construction is gypsum wallboard as a part of a gypsum drywall system. Gypsum drywall is a common material used for the covering of timber and steel stud framing. The base of the wall finish system is wallboard consisting of gypsum slurry solidified into large paper-skinned panels (4 foot by 8 foot is standard). The wallboard is usually connected to the supported framing by mechanical fasteners (nails or screws), although adhesive has occasionally been used. Following attachment, the remaining operations are taping and compounding of the joints, texturing (when desired), and painting.

**Common Practice of Gypsum Drywall Installation**

Wallboard was originally developed in the late 1880’s by Augustine Sackett (California State Department of Education, 1972, pp.13). At the time spackling material was used to fill the joints, which were then taped with muslin cloth. The wallboard was square-edged and time consuming to cover the joints with these materials. Gypsum wallboard and joint compounds were greatly improved starting in the late 1920’s. Highly calendared ivory paper replaced the previous covering paper. Paper fibers were added to the basic core material. Wallboard with tapered edges was made. Perforated paper tape and specialized joint compounds were made that allowed for faster and easier closing of the joints. Later mechanical taping and finishing tools were developed. Joint compounds have continuously been improved for workability and durability.

In the 1950’s construction using wallboard became more popular, as did another wall finish using gypsum lath (button board). Gypsum drywall continued to gain in popularity until in the 1970’s about 90% of new residential construction was made using gypsum drywall for interior walls and ceilings (California State Department of Education, 1972, pp.13). This increased usage is based upon various advantages of the drywall system: sound control, speed and relative cleanliness of construction, availability of attractive and unique final finishes. Today drywall is widely accepted in residential, commercial, industrial, and institutional construction.

Various components make up a drywall system: the supporting framing, the gypsum wallboard, the joint tape and the joint compound. Different methods of installation are used, from the relatively labor intensive manual installation to the high production mechanical installation methods. Manual installation is performed using trimming knives, wallboard hammers, and
spackling broad knives. Mechanical installation uses power screwdrivers, nail guns, automated taping systems and compound applicators.

A survey was conducted of subcontractors to supplement the knowledge gained from the available literature. The questionnaire in Appendix A was mailed to 67 local drywall contractors in the San Jose area, identified through the local phone directory. A total of 19 replies were received, a response rate of 28%. The results of the survey show a wide variety of drywall practices for residential construction. The survey identified drywall screws as the primary means of attachment and paper tape as the dominant means of supporting the drywall joint. Screw spacing, stud material and topping compound were seen to vary between several options. Further details on the survey results are given later. Testing of the fatigue strength of wallboard screws has been conducted and indicates that at service level loads the screws do not have significant change in behavior for well over 10,000 cycles of loading (Konig, 1989, page 238). At higher levels of loading (80% of the static strength), the slip was significant in the first few cycles of loading, but then increased minimally over the next twenty cycles.

Testing of Gypsum Drywall Specimens

Testing of wall systems is usually conducted following the protocol defined by the American Standards of Testing and Materials Specification E 564-94 (ASTM, 1994). Important engineering parameters include ultimate shear strength, shear displacement, and shear stiffness. These values are usually reported for a unit length of wall, where the typical wall specimen height is eight feet.

Testing of drywall systems has been conducted by various institutions and a comparison of the typical engineering parameters measured in the tests is shown in Tables 1 and 2. The strength and stiffness reported here have large variability, primarily because of differences in the specimens, e.g., different thicknesses, different kinds of connectors and connector spacings, and different framing (wood versus steel stud). Details of the test specimens are below.

APA Tests: The American Plywood Association (now APA, the Engineered Wood Association) has a long history of testing wall systems for residential construction. One report (Adams, 1974, pp. 23-26) discusses several wall types, including those with gypsum wallboard. Test Series 5 included gypsum wallboard alone and in combination with plywood as listed in Table 1. The objective of this test series was to determine the performance of various constructed walls built from plywood. Gypsum wallboard was included in the study because of its prevalence as a means for fire-resistance.

The test specimens were 8-feet high and 8-feet long. Test protocols appear to be forerunners of the current ASTM standards. Attachment was by drywall nails measuring 1-1/4” long, with 0.098” diameter, annular ring nails with 0.25” diameter heads. The study compared bare gypsum wallboard to systems with both wallboard and plywood, and the behavior of the two component systems appeared to be additive.
Karacabeyli & Ceccotti Tests: Karacabeyli and Ceccotti (1996, pp. 2-179 to 2-186) report on a series of shearwall tests, including specimens built from plywood sheathing, 3/8” oriented strand board, and/or 1/2” gypsum wallboard, Type X. Four specimens of particular interest to this report are listed in Table 1. The test specimens were 8-feet high and 16-feet long with framing studs spaced at 16” on center. The top edge of the wall was restrained from vertical movement and actuators were used to produce a vertical load on the wall. Walls were horizontally blocked at mid-height, and wallboard was attached with either 1-1/4”-long screws or 1-1/2”-long roofing nails having a diameter of 1/8” and head diameter of 0.4 inch. Both screws and roofing nails were placed at 8 inches on center around the perimeter and 12 inches on center on the interior framing supports. Test specimens were loaded either monotonically or with increasing-displacement cycles. For cyclic tests, each displacement-control level was repeated three times to determine a stable relationship.

The reported findings included several issues related to the current project. Defining a yield point was found to be difficult because the load-deflection curves were nonlinear from very low loads. The goal of the project was to determine reliable information for the use of gypsum wallboard as a lateral force-resisting element of a building. To obtain these values, the authors suggested that the results from monotonic (ramp) loaded specimens be adjusted with undetermined factors to account for strength degradation due to cyclic loading. The authors refer to a “stabilized cycle”, defined as a third cycle at a given displacement level, to develop backbone curves of the cyclic test specimens.

The K&C test program was one of the few reported studies where gypsum wallboard was tested in a wall system combining gypsum wallboard and oriented strand board. In specimens combining these two materials, the superposition of wall material strength and stiffness (oriented strand board and gypsum wallboard) was found to hold up to a lateral displacement of 1.25 inch (1.3% drift). Beyond this, the wallboard contributed to higher stiffness and peak strength but less post-peak ductility, compared to specimens with oriented strand board alone.

Oliva Tests: Oliva (1990) reports cyclic and monotonic tests of gypsum wallboard systems. Wall panels measured 8-feet by 8-feet with 2x4 wood framing. All frames were sheathed on one side by 1/2 inch thick gypsum wallboard. The gypsum board was connected to the framing by 1-1/4 inch drywall nails spaced 8 inches on center over all framing members. Restraints were applied in the form of 2 anchor bolts at the bottom and top, and a vertical (axial) load of 450 plf was applied to simulate the gravity loads in the wall. Repeated test were carried out on the specimens for monotonic, static-cyclic and dynamic loads. Dynamic cyclic tests were conducted at loading rates with a frequency of 5 Hz.

Though this project gives only the strength and stiffness characteristics at the global level as the final results, the important aspect of this research from the point of view of this project was that it describes the damage patterns in the wall, i.e. the nails that failed and caused failure. Oliva also proposes a model for the monotonic as well as cyclic nonlinear behavior of the panel.
Shown in Figure 1 is a comparison of the typical load versus deformation response of the static monotonic and cyclic tests by Oliva. During the monotonic tests, the wall gradually softens. For the cyclic tests, the initial stiffness is about the same as the monotonic tests, but the stiffness degradation in subsequent cycles was rapid and, as shown in Figure 1, the envelope of the cyclic response lies inside that of the monotonic tests. No other specific stiffness data, besides the plotted load-deformation response, was reported for the cyclic tests.

Oliva describes in detail the observed damage thresholds in the monotonic and cyclic static tests. The damage can be generally categorized by two level, A and B, where A denotes “Visual Damage in the form of cracking and spalling of the joint compound above sheathing nail heads” and B denotes “The tearing of nail heads through the paper surface”. A summary comparing these damage thresholds to the wall drift and load level is given in Table 3, and Figure 2 shows the typical pattern of nail damage. In Table 3 we see that the maximum load of 245 lb/ft for the monotonic tests reduces to about 170 lb/ft for the cyclic tests. To summarize, it was observed that the type of test (i.e. monotonic or static cyclic) has an important effect on the response of the wall. The maximum load capacity under the cyclic loading was found to be about 70% of the capacity under monotonic loading. The initial stiffness was found to be similar in both cases but the deterioration of strength and/or stiffness occurs more rapidly in the cyclic test. The damage modes are the same in monotonically and cyclically loaded walls, except that the damage threshold displacements are about 50-70% less in the cyclically loaded specimens. Numeric values for damage, strength and stiffness are not reported for the cyclic dynamic tests, however the response to dynamic loading was not much different from their response to cyclic static loading.

Oliva also reports data from tests on glued walls, where the walls have been glued as well as nailed to the wooden framing members. The tests on glued walls showed that the strength and the stiffness of the glued walls were much higher than that of the nailed walls. The initial stiffness of the glued walls was 230% that of the nailed walls, and maximum strength of 280 lb/ft was 160% of the strength of the nailed wall under similar conditions. The load displacement relationship can be seen in Figure 3.

It was also observed that the damage modes and thresholds are very different for glued versus nailed walls. The nailed walls showed mainly damage around the nails in the form of popping of nails and spalling of paint and nails tearing through paper. Apart from this, the glued walls also showed a combination of cracking of gypsum and the delamination of the glued paper surface from the gypsum. In addition, the initial damage in the glued walls was delayed as compared to the nailed walls, i.e. the initial visible damage in the glued walls occurred at 1.5-2.0 times the corresponding displacements as in the nailed walls. Also, the damage in glued walls was much more localized than the damage in a nailed wall and hence Oliva suggested that repairing the glued walls might be more economical than repairing the nailed walls. The damage can be seen in Figure 4. Finally, contrary to their other advantages, the glued walls were found to be more brittle than the nailed walls. As shown in Figure 3, the resistance of the wall drops rapidly in the
higher stages of loading, and Oliva suggests that in severe cases this may bring about a brittle and sudden failure mechanism of a building.

**Merrick:** Merrick (1997) investigated gypsum wallboard under load-controlled cyclic testing of wall assemblies. The wall systems consisted of plywood, oriented strand board, and/or 1/2-inch gypsum wallboard. The wallboard specimen was 8 feet high and 13'-1” long with wallboard on both sides of the specimen. The wallboard was attached with 1-5/8”-long wallboard nails with a shank diameter of 0.086 inch and a head diameter of 0.281 inch. Wallboard was installed with the panel vertical, allowing for all edges to be blocked. Horizontal load was applied at the top of the wall and the wall was anchored using commercially available hold-downs.

These tests were done under cyclic load control, at rates approaching dynamic loading (5 cycles per second). Relevant test specimen results are shown in Table 2 (M-GB1-B, and M-GB2). The walls failed as the edges of the gypsum panels weakened and allowed the nails to pull through the face of the panel. Due to the force-controlled testing, lateral displacement was recorded to drift levels far beyond usable limits.

**Zacker and Gray:** Testing of 8-foot by 8-foot gypsum wallboard systems was included in a series of tests of plywood shear walls (Zacker and Gray, 1985, p 44). Four specimens of one-sided gypsum shear walls were built. It is believed that these specimens were built from ½-inch wallboard. Wallboard was installed with the panel horizontal and without blocking. The walls were tested with cyclic dynamic loading, with gradually increasing levels of maximum displacement. The researchers noted that the walls failed by cutting of the wallboard and with minimal damage to the nail fasteners. In addition, they noted that the resistance to lateral force was originally provided mostly by the nails at the extreme corners of the wall. As these highly loaded nails failed, the nails closer to the mid-height of the wall resisted load. One recommendation from the testing was that the strength of gypsum sheathing should not be added to strength of plywood sheathing for a given shear wall.

**Other Wall Panel Tests:** Projects by Miller and Pekoz (1994), Adham et al (1990), Rihal and Granneman (1984), Thulin (1983) and Rihal (1982) deal with metal framed partition walls, and so are not exactly the systems we deal with in this project, however, we can review these to draw some conclusions. The project by Freeman (1977) involved the testing of steel framed and wood framed partition walls. From his paper, it was seen the stiffness values obtained from the two cases are a little different, i.e, the stiffness for the metal frames was about 75-80% of those for the woodframes. However, after studying Oliva’s tests, one observes that the frame stiffness contributes to only about 5-10% of the total stiffness, so the difference in stiffness here may be a result of the type of connectors (nails as opposed to screws). The stiffness values for the wooden frame obtained from these tests are quite similar to those obtained by Oliva in his tests, also, the stiffness values obtained for the light-gage metal frames are quite similar to those obtained by Rihal. It is believed that the behavior of the fastener in the framing may be a significant factor in the change in stiffness. When a screw is installed into a wood stud, the penetration into the stud
results in a rigid support (essentially the screw is a cantilever supported by the stud). When installed into a steel stud, the screw is only held by the thickness of the cold-formed steel. This results in behavior more similar to a pin support, where the screw is able to rotate in the plane of the fastener.

Despite the variation in the types of tests conducted that have been reviewed, and the scatter in the results of those, a few general observations can be made. The damage levels (as a function of story drift) are not very sensitive to the type of frame (steel versus wood) or the thickness of the wallboard. On the other hand, they are somewhat sensitive to the type of connection (nail versus screw). The initial damage threshold, characterized by excessive deformations around the connectors and/or spalling of paint over the nails or screws, occurs at somewhat higher drifts in walls with screw as compared to nail connectors. For screwed connectors, the damage displacement was typically 0.25 to 0.35 inch (drift ratio percentages of 0.3 to 0.4) versus thresholds of about 0.1 to 0.2 inch (0.1 to 0.2) for walls with nail connectors.

**Contractor Survey**

A written survey was conducted of industry personnel to provide additional information about the construction of wall systems. The majority of surveys were sent to drywall sub-contractors listed in the phone directory for San Jose. In addition, surveys were distributed to design professionals familiar with drywall installation. A total of 67 surveys were distributed and a total of 19 were returned and analyzed. The survey is included in Appendix A of this report. Of the respondents 11 were subcontractors, 3 were drywall retailers, 3 were engineers and 1 was an architect. The average respondent had been involved in the industry for 25.8 years. The respondents wrote that their responses represented tract housing, custom home, multi-family and commercial construction.

Typical wallboard thickness was essentially split between 5/8 inch and 1/2 inch, with 5/8 being indicated more often. Other reported thicknesses were 3/4 inch and 1 inch. The initial fastener used to hold the wallboard in place was either drywall screws (11 responses) or phosphorus coated nails (7 responses). When asked the type of fastener used to complete the attachment of the wallboard to the framing, the use of screws increased (15 responses to 3). The spacing between fasteners along the edge of the panel was 8 inches (10 responses), 7 inches (5 responses), 6 inches (3 responses) and either 12 inch or 16 inch (1 response each). Typical field spacings were given as 12 inches (9 responses), 8 inches (3 responses), 7 inches (3 responses), and either 18 inch or 24 inch (1 response each).

Reinforcement for the joint was given as paper tape (17 responses) or fiberglass strip (2 responses). Joint embedding compound was either all-purpose compound (12 responses), or vinyl ready-mix or quick-setting compound (3 responses each). The joint topping compound was vinyl ready-mix (10 responses) all-purpose compound (4 responses), or quick-setting compound (3 responses).
Engineering of residential construction in California is generally governed by the guidelines of the Uniform Building Code. As wallboard replaced plaster as the primary method of finishing interior walls, the material began to be used as a means of resisting lateral forces. In the 1955 code (International Council of Building Officials, 1955, p89), gypsum sheathing is listed as a means of finishing, but is not assigned a lateral strength. Later, woodframe structures were designed where gypsum wallboard systems provided the lateral support for one-story single-family residences. In recent years the shear strength assigned to wallboard has been decreased significantly in seismic zones 3 and 4, as a result of experimental test data (Zacker and Gray, 1985, p 44). This reduced strength requires longer lengths of drywall to resist seismic loads. This has limited the ability of structures to be designed using only drywall as the lateral force resisting system.

Currently the 1997 Uniform Building Code defines a unit-strength of 150 lb./foot for 1/2-inch, blocked with 4” nail spacing gypsum drywall shear walls. This value is reduced by 50% for seismic zones 3 and 4. The resulting design strength (75 lb./foot) is so small that its contribution is often dismissed during design. The strengths are for allowable strength design, and include factors of safety. Note, however, that these nominal strengths specified by the UBC are significantly less than the strengths reported in the literature of 170 to 640 lb./foot.

FEMA-273 (Federal Emergency Management Agency, 1997) provides guidance on the seismic behavior of many structural systems, including light frame wood shear walls. It discusses wall finishes and provides estimates of the force-displacement relationship for some of these materials. Like the UBC values, the specified nominal strengths of gypsum wallboard are significantly less than the average test data.

Non-engineered woodframe construction is identified as conventional construction in the Uniform Building Code (International Council of Building Officials, 1997). This prescriptive section of the code defines maximum wall spacing and limited information about fastener requirements. However, the industry appears to follow these requirements loosely, and thus guidelines from this portion of the building code may not necessarily be representative of actual practice.

Guidelines on damage state criteria were found for gypsum-roof diaphragms (Kunnath et al., 1994, pp. 124-125). Damage was defined as three levels: minor, moderate and major. Characteristics of minor damage included: no loss of strength or stiffness, repair recommended but not required, and interruption to building function very low. For the reported study, if diaphragms received less than 0.0025 shear strain, the damage would be categorized as minor. Moderate damage characteristics included: some loss of seismic resistance, repair would be mandatory, and partial evacuation may be required. This damage state had an upper threshold of shear strain of 0.0050. Major damage, which correlated with shear strains over 0.0050, had the characteristics of: significant structural damage, potential collapse possible, total evacuation of the structure, and that the structure may be repairable but might also be condemned.
Portland Cement Construction

An alternative wall finish to gypsum wallboard is the coating of supporting members with a cementitious material made of sand and Portland cement. The scope of this research project originally considered the evaluation of Portland cement wall finish materials. As the research progressed, this feature was removed from the scope of work. This portion of the literature review is included to permanently document the literary research reviewed. The authors hope that the review may be of assistance to other studies, even though its’ relevance to this report has been reduced.

Wall systems of this type are officially titled Portland cement plaster, but also commonly referred to as stucco by the general public. Cement can be supported by gypsum lath, wood lath, or interwoven wire. Some form of framing, often lumber, holds the supporting material. Cement plaster was a common interior wall finish until gypsum wallboard became commonly available. Since the rapid growth in interior use of gypsum drywall, plaster and Portland cement have become limited to exterior wall finish today.

The wall system has four primary components: Portland cement plaster, reinforcing mesh, membrane, and wood framing (Dost and Botsai, 1990). Plaster should be made from Portland cement with a 2.5-inch slump. Similar to concrete, plaster shrinks as it cures. It is desired that the cracks caused by shrinkage be several small hairline cracks rather than a few large ones. Large cracks are usually a result of uneven thickness of the plaster. Plaster is applied in at least three coats, first a scratch coat, second a brown coat, and finally at least one finishing coat. The reinforcing mesh can be of various weights and strength. One recommendation is the use of galvanized 1-1/2 inch 17-gauge wire mesh. This mesh can be installed on the wood framing using furring nails to allow for proper placement of the mesh in the plaster. The membrane is a heavy-duty material; the use of #30 felt was common, but currently two layers of Grade D paper is the industry standard. Alternatives to the wire and felt membrane include self-furred, paper-backed lath and less commonly recommended factory-laminated felt/paper system. The bottom edge of the wall is trimmed with a drip screed to allow for the weepage of moisture from the wall. When walls are built without sheathing, line wires are used to support the building paper during application of the stucco.

There are disadvantages to the use of plaster, in addition to the potential problems with shrinkage cracking mentioned above. During application, sand/plaster introduces significant moisture to the structure, increasing the chance of warpage of the wood framing. Another disadvantage to stucco is the potential delay in construction time due to the drying time between the multiple coats of plaster. A third disadvantage is that the thermal expansion of plaster is not consistent with that of lumber, leading to the formation of thermal expansion cracks. For all of these reasons, plaster is often cracked before an earthquake event. One recent change to plaster construction has been the use of glass or polypropylene fiber to reduce cracking.
Construction of plaster wall systems can be made using the line-wire installation technique. When properly constructed the resulting system allows for limited slip to occur between the plaster skin and the lumber framing. This slip is made possible by the introduction of a slip sheet between the membrane and the plaster during construction. This slip sheet can be almost anything, including newsprint or Grade D building paper.

Information for the engineering behavior of Portland cement, plaster, or stucco wall is available from the International Council of Building Officials. The strength listed for the 1997 UBC is 180 lbs./foot for 7/8-inch thick plaster on unblocked walls with nails spaced six inches on center. This is a reduction from the values given in the 1955 UBC of 675 lbs./foot for 1-1/2 inch thick plaster (International Council of Building Officials, 1955). As can be seen, the allowable design strength varies significantly for these walls, based upon the year of construction.

The FEMA 273 (Federal Emergency Management Agency, 1997, pp. 8-19) document provides a force-displacement relationship for Portland cement walls. In addition to the shear strength of 350 lb./foot, the guidelines recommend a strength reduction of 80% after the deflection ductility at full strength is reached. Considering no deflection of the anchorage and a shear modulus of 14,000 lb./in., they recommend a yield deflection of 2.4 inches for an eight-foot tall wall. Deflection ductility at full strength is given as 3.6 for wall aspect ratios of 1.0 and 2.5 for wall aspect ratios of 2.0. Likewise an ultimate deflection ductility of 4.0 is recommended for the stout walls and a ductility of 3.0 for the slender walls.

**Cost-Damage Relationships Available in Literature**

Economic cost is an important measure of the damage from earthquakes. This monetary representation reflects the direct economic loss that a region will receive, and can be used to estimate insurance levels and to compare relative risk mitigation programs. Information has been collected about the damage levels of historic earthquakes and the costs associated with relative tasks of construction and reconstruction. In addition it is crucial to global risk management strategies that the total value of existing structures and their relative materials be established. Although this global risk evaluation is beyond the scope of this task, relevant information is presented here as a starting point for a more ambitious project in the future.

**Cost Estimates from Past Earthquakes**

During the 1971 San Fernando Earthquake damage to residential construction was substantial and post-earthquake investigations reviewed 12000 residential structures (Oakeshott, 1975, pp. 329-334). In their report they categorized building damage as being severe, moderate or slight. Severe damage represented buildings with permanent distortion, separation of the framing from the foundation, portions of the plaster were loose or had broken free, wallboard required replacement or retaping of the joints, and/or roofs at incipient collapse. Slight damage indicated minor cracking of the wall finish material, the enlargement of pre-existing cracks, or repair could be achieved by spackling of the plaster or wallboard. Structures were rated moderate when they appeared between these two extremes.
Of the structures reviewed, 78.0% were rated with slight damage to interior gypsum wallboard, with 6.5% rated moderate, 3.4% rated severe, and 12.1% with no damage. Likewise 78.4% were rated with slight damage to interior plaster, 11.1% rated moderate, 6.3% rated severe, and 4.2% with no damage. As for exterior stucco finishes, 74.1% of the structures were rated slight, 4.0% were rated moderate, 1.2% were rated severe, and 20.7% were rated with no damage. In addition, the investigators found a strong correlation between the ratio of damage cost to pre-earthquake value and whether the construction was pre-1940, two-story dwellings, and dwellings combining both one and two story portions. Of the categories, combination one and two story dwellings showed the most damage, two-story dwellings were next worse, and pre-1940 construction was third.

**Relative Cost of Wall Construction Components**

The Department of Commerce (1992) publishes construction industry cost statistics on a 5-year cycle. The 1992 census reports on the value of construction conducted by various special trade contractors. The census is divided into various specialties: acoustical ($1.5B), carpentry ($0.1B), drywall ($6.6B), insulation ($3.1B), lathing ($0.5B), painting ($0.1B), and plastering ($1.4B) for a combined total of $13,438,000,000 of subcontracting. The census was based upon the value of work done by subcontractors in loosely defined categories. The total value of work performed would include several items besides wallframe construction, such as ceiling construction and reported subcontractors may do work outside of their primary business.

If it is assumed that the relative costs of wall construction was comparable to the distribution of total work, then the values reported can be used as an estimate of the relative cost of various portions of the drywall system. In 1992, from the $13.4 billion total cost, $6.6 billion went to drywall, sheetrock, spackling and finishing subcontractors (49.3%), $1.4 billion went to plastering contractors (10.4%). Thus, according to these economic statistics, drywall comprises almost a 5 to 1 ratio of the wall finish construction market when compared to plaster. In comparison to the wall materials, the painting subcontractors accounted for $0.12 billion dollars. Thus, for new construction it would appear that of the total cost of building and painting wall frames ($8.12 billion), the cost of the painting was only 1.5% of the cost of the wall finishes.

Extrapolating these estimates to repair work may or may not be appropriate. In new construction, painting can be done before trim, windows, doors and floor finishes are installed. It can also be combined with wallboard texturing. Painting of an existing wall will require time and labor to protect these nearby items. This makes repair painting very labor intensive and hence proportionally more expensive.
Chapter 3. Experimental Test Program

Objectives of Experimental Testing

Task 1.4.6 had several specific goals and objectives as discussed in Chapter 1. The testing program was intended to provide experimental data to be reviewed as a means of meeting these items. This data would be reviewed to allow for analytical and empirical development of engineering guidelines for future woodframe construction.

The objectives of the experimentation were:

1. Record photographic evidence of the damage thresholds for varying levels of drift.
2. Compare the performance of walls using screws or nails to support the wallboard and evaluate the effect of different fastener spacings.
3. Compare the behavior of the walls for monotonic or cyclic loading protocols.
4. Compare walls built using floating edge construction (no fasteners within the top eight inches of the wall) with walls built with fasteners at the top plate.
5. Compare walls where the top of the wall deforms laterally without vertical deflection to walls where vertical deflection is allowed.
6. Compare the influence of window openings on the behavior of the wall.
7. Compare the effect of building walls with butt-joints placed in the location of openings to walls where the butt-joints are located away from the opening.
8. Determine if simple alterations to the construction process results in improved engineering performance.
9. Evaluate the performance of walls that are damaged, repaired, and reloaded.

Test Specimen

Seventeen wall specimens were tested to determine the effects of seismic loading on the response behavior of gypsum wallboard sheathed walls. All test specimens were built with the following specifications, unless specifically noted elsewhere. The walls were all 8 ft. by 16 ft. (2440 mm by 4880 mm) size and framed with 2 in. by 4 in. (50 mm by 100 mm) nominal dimension lumber. All framing lumber was Grade #2 or better, Hem-Fir. The lumber was laid out in the manner show in Figure 5. The frames have double top plates, single bottom plates, 4 in. by 4 in. (100 mm by 100 mm) endposts and intermediate single studs at 16 in. (406 mm) on center. All frames are sheathed on both sides with Standard grade, 1/2-inch (13 mm) gypsum sheathing.
The 4x8 foot (1220 mm by 2440 mm) sheathing panels are applied to the wall horizontally because previous research had shown that application to have superior strength. In addition, horizontal application of the wallboard appears to be the industry norm; in fact the use of 4x12 foot sheets is growing quickly. Except for the proprietary wall finish for one test, all materials were purchased at local retail outlets.

A framed door opening was located at the same location in all walls. A second type of specimen was designed to allow for variation in the configuration of wall openings. Type 2 is shown in Figure 6 to allow for both a door and window opening. The panels of wallboard were also alternated on different sides of the test specimen. Figure 7 shows the orientation of the panels for both the front wall and back wall of each specimen. The report’s photographs are predominantly from the front wall, mostly because of the clearer access to this face.

One comment received from industry was the suggestion that Douglas Fir/Larch was more likely to be used in residential construction. There are two primary differences between these two species of wood: the fastener withdrawal strength and the lateral bearing strength. The materials were purchased from a local lumberyard. This yard has the benefit of storing the lumber indoors, allowing for the wood to be bought with a low moisture content. At the time of purchase, two types of lumber were available: Hem-Fir #2 or Better or Douglas Fir/Larch Select Structural. Because the knotting and wood quality of the Hem-Fir is closer to the Stud grade commonly used for construction, it was decided to select the Hem-Fir for the specimens.

It was believed that one of the key causes of damage to the wallboard is the influence of intersecting walls and the ceiling. These perpendicular elements tend to restrain the movement of the sheathing panels relative to the framing. Since the wallboard is taped and compounded to these orthogonal elements, cracking and/or crushing of the wallboard is expected to occur at lower levels of drift. To simulate this three-dimensional behavior, the walls were built with boundary members along the top, bottom and both ends, as shown in Figure 8. The top and end boundary members were 2x lumber. Mounted on this lumber was 1/2-inch or 3/8-inch wallboard. The thickness of these boundary members was changed midway through the test program, as the dimensions of the boundary made it difficult to fit the in-plane panels into the specimen. The bottom boundary was 2x lumber without covering. By design, a 1/4-inch gap was left between the wallboard and the bottom lumber, although measured values after construction varied from no clearance to as much as 0.6 inches.

The wallboard joints were taped with paper and finished with three layers of all-purpose wallboard compound. Two coats of flat, latex paint were applied after the compound was dried and sanded. No surface texturing materials were used. Laboratory technicians and student assistants built the wall specimens, with guidance of the construction by a licensed California contractor. Figure 9 shows the framing built for Type 1 specimens. Figure 10 shows the connection between the actuator, the loading steel channel (drag element) and the wall’s double top plate. The channel was connected to the top plate in three locations: at each end and in the center of the wall, as shown in the sketch of the figure. Carriage bolts were used to connect all of the elements together. Figure 11 shows one of the reaction supports at the end of the
foundation. This support resists horizontal force along the base of the wall and identical supports were placed at each end of the wall. Figure 11 shows the 2x6 flat support and the 4x6 support standing underneath. The 4x6 was restrained from sliding only by the steel reaction supports shown (no bolts were installed connecting the 4x6 directly to the rigid steel frame. Figure 12 shows the specimen for Test #1 after taping and compounding and before painting.

Test Variables

The test specimens were designed to represent standard construction of gypsum wallboard partition walls. Table 4 lists the full test matrix and the features of each individual test specimen. The test variables considered in the design of the specimens were:

1. fastener type,
2. fastener spacing,
3. loading protocol,
4. the use of floating edge construction,
5. the ability of the middle of the wall to move vertically during lateral deformation,
6. the addition of a window opening,
7. the layout of panels on a wall,
8. the potential influence of innovative construction techniques,
9. the performance of walls after being repaired,
10. and the influence of a door frame, door trim, and baseboard.

The Uniform Building Code, Volume 1 (International Council of Building Officials, 1997, page 270) lists minimum fastener requirements in Table 25-G. These values are the same as those provided by ASTM C840 (ASTM, 1995) and the Gypsum Association’s Publication GA216 (Gypsum Association, 2000). Table 5 lists the fasteners and the spacing used for the tests. The nail size and spacing, the screw size, and the 16-inch spacing for screws are the minimums required by the Uniform Building Code. The eight-inch screw spacing was intended to represent a lower bound on the spacing of screws for residential construction.

Three loading protocols were used: two monotonic and the CUREE-Caltech Woodframe Project cyclic protocol. For the first monotonic protocol, the wall was loaded to a maximum drift of 4%. At this point, the loading was reversed to a peak drift of 4% in the opposite direction. This 4% limit on the frame was chosen to represent a level of distortion that would be beyond repair and likely in a collapse state. After testing it was observed that very limited additional damage occurs when the drift exceeds 3%. In addition the maximum drift was set as a precaution of damaging
the wood framing excessively. This allowed for the majority of wood framing to be used for several tests.

The second monotonic loading protocol was developed during discussion of the design of the test program. From an engineering viewpoint, it was desired to know if unloading stiffness could be used as a means of evaluating the remaining strength and stiffness of the wall. To allow for such future study, the applied displacement was reduced at certain points during the test to measure the unloading stiffness. This protocol was used for Test #8 and Test #9. Unloading was performed after photographs were taken at drift levels of 0.75, 1, 1.25, 1.5, 2, and 3% drift. The applied displacement was reduced until the resisting load was less than 1000 pounds. Displacement was reapplied and the wall was returned to its’ initial maximum deformation. Except for these unloading and reloading steps, the protocol was identical to the original monotonic protocol. It is believed that the behavior of the two walls was minimally affected by these unloading and reloading excursions.

Task 1.3.2 developed the cyclic loading protocol for the CUREE-Caltech Woodframe Project (Krawinkler et al, 2001). The cyclic loading protocol was based upon the drift at the time that the load drops to 80% of the peak load resisted in the standard monotonic test. This displacement is denoted as $\Delta_M$. To establish this standard, Test #5 was chosen as the specimen closest to the norm of common wall construction.

Once $\Delta_M$ was determined, the cyclic protocol was based upon a drift of $0.6\Delta_M$. This drift is expected to represent the drift at the peak load. The cyclic protocol was then defined from this sole value, and was constructed of several primary and trailing displacement-controlled cycles. The loading protocol was completed when the interstory drift exceeded four percent. At this point, the first primary cycle over four percent was applied and followed by two trailing cycles. A second primary cycle was applied with a drift identical to the prior primary cycle. Although there were several distinct specimen designs, only a single cyclic protocol was defined. This was done to allow for easier comparison of the results. Table 6 and Figure 13 show the cyclic protocol displacement control.

The influence of dynamic effects on the specimens was not within the scope of the test program. To allow for static loading conditions, the horizontal load was slowly applied. Tests took approximately two hours for monotonic loading protocols and four hours for cyclic loading protocols. The fastest load applied during a test was approximately a quarter of percent drift per minute. Loading was stopped at predetermined levels of drift to allow for photographic documentation of the damage states. These stops would take approximately ten minutes and the lateral deflection of the wall would remain constant.

Another test variable was the method that the top plate was attached to the wallboard. Floating edge construction has been recommended by the gypsum wallboard industry for over twenty years to minimize partition separation problems. Various factors contribute to partition separation problems, including soft soils, soil freeze-thaw cycles, and fluctuations in high water tables (Grundahl, 1997, page 36). This construction method is to allow for in-plane movement of the vertical wall without causing cracking of the ceiling-wall intersection. Additional reasons
reported for the use of this construction method include: control of cracking due to lumber shrinkage, control of cracking due to movement of roof trusses, and the ability to construct inside corners more accurately.

Floating edge construction allows for the elimination of fasteners from the top several inches of the wall, according to Section 2511.3 of the 1997 Uniform Building Code (page 264). The Code allows a region of 8 inches for wallboard that is fastened with nails and 12 inches for wallboard that is attached by screws. Floating edge construction appears to have limited use in California, according to informal discussion with industry personnel. One reason for this limited use may be that the factors listed by Grundahl are less critical in warmer, dryer regions of the country. For this series of experiments, two methods of attachment were used: for floating edge, no fastener was placed within the distance specified by the code from the top of the wall, and for common practice the fasteners are attached along the uppermost plate directly above each framing stud.

Two means of vertical restraint were envisioned for a typical residential home. The ends of a wall are typically attached to intersecting walls. Vertical uplift of the end of the wall would thus require vertical lifting of these attached walls. The second means of restraint would be the members supporting the floor above. Top floors are expected to deflect laterally with little resistance to vertical motion of the gypsum wallboard. This is due to the light gravity loading that truss roofs or other roof framing systems provide on the wall. In addition, these trusses may be installed with clip angles containing vertical slots for minimal resistance to vertical movement. On the other hand, lower floors of multi-story homes resist significant gravity load, especially when walls are located directly below upper floor walls. A pair of 1-3/8-inch diameter anchor rods was installed at each end of the wall to simulate the vertical resistance provided by the intersecting walls. To allow for testing of the two options of vertical resistance along the top of the wall, an additional pair of anchor rods was installed in the middle of the wall when a fixed vertical boundary condition was desired. A steel channel linked each pair of rods; this channel was perpendicular to the loading channel shown in Figure 10. Before testing all anchor-rod were tightened to an axial load of 2000 pounds via a calibrated torque wrench. No monitoring of the force in the rods was done during the testing, although at the end of the test, significant force remained in the rods as it required comparable torque to remove the tightening nuts.

The potential influence of a window opening was also of interest. A standard window-frame opening as shown in Figure 6 was built into the framing for Tests 10, 11, 12 and 13.

Different methods of installing wall openings are often used in construction. When large-production drywall contractors hang wallboard, they often cover the entire wall and then return and cut the doors and windows at the openings in the framing. This implies that the butt-joint, when two ends of wallboard meet, is often not in the near vicinity of the opening. Other builders cut the openings into the wallboard before hanging. When this second method is used, the gypsum industry recommends that the butt-joint then be placed somewhere away from the corner of the opening. Figure 7 shows the layout of panels for the test specimens, the front face was built placing the upper butt-joint in the center of the door opening and staggering the vertical joint in the lower row of wallboard. This layout resulted in the upper row of panels having a butt-joint
at the corner of the window opening. The back face of the wall was built with the butt-joint in the middle of the wall, away from the openings.

To reduce the long-term cost of wallboard systems, it was desired that potential innovations be tested. The ideas tried include: larger heads on the screws, fiberglass joint tape to reinforce the wall openings as shown in Figure 14, and wall coverings made from more ductile materials.

Testing for the behavior of walls that have been damaged and repaired was also included. This information will allow engineers to determine if wall systems must be demolished and replaced or if repair can produce suitable post-repair behavior. For these tests, walls were loaded using the cyclic loading protocol until the first complete primary cycle at $0.6\Delta_M$ was completed. The wall was then returned to a plumb condition and repaired by compounding cracks, retaping joints, replacing small portions of panels if necessary and repainting. The repaired walls were then tested to failure using the original loading protocol.

The final test variable considered was the influence of a door frame and trim. Test #17 was built identically to the standard Test #5, except a door frame was installed in the door opening, door trim was nailed along the perimeter of the door opening, and baseboard was nailed along the bottom of the wall, as shown in Figure 15. These additional pieces were added after the wall had been taped, compounded and painted.

**Test Instrumentation**

Instrumentation was mounted on the specimen to record quantitative data for various parameters. **Table 7 and Figure 16** list the various channels, the parameter measured and the type of instrument used. Additional data collected was the instrumentation input voltage for each data step. All data channels were scanned every five seconds. In addition, qualitative data of still and digital photographs were taken to allow for subjective evaluation of the specimen performance.

**Construction of Test Specimen**

The specimens were built and tested in 2000 and early 2001. Framing nails were driven with a nailing gun. Drywall nails were driven manually with a drywall hatchet hammer. Screws were driven with an electric drywall screw gun with calibrated torque cut-off switch. After driving, each screw was manually tightened with a standard Phillips screwdriver to verify correct installation.

Nails were used for the first specimen and during the construction of this specimen, some nails appeared to have been overdriven, thus resulting in the paper surface of the wallboard being torn. These nails were not replaced, thus the total number of nails was similar to that of a final wall. For all other specimens, overdriven nails or screws were identified and replaced. When possible, the over-driven fastener was removed if damage to the wallboard could be minimized. When severe damage to the wallboard appeared imminent, the fastener was left in place. All replacement fasteners were installed within two inches of the overdriven fastener.
The wallboard joints were taped using paper tape; joints and nail heads were then covered with three layers of all-purpose joint compound. Compound was sanded after each layer dried. Flat, off-white, latex interior paint was applied in two coats on successive days (Hop, 1988, pp. 289-316).

**Innovative Systems**

One objective of the test program was the attempt to build wall finishes that would resist larger drifts with less damage. Two tests were designed, built and tested to meet this objective: Test #12 and Test #13.

**Alternative Screws and Reinforced Corners**

Test #12 was intended to be a cheaper alternative. It used standard wallboard but replaced the standard wallboard screws with screws that had larger heads. Two different screw types were tested, one on the front face and another on the back face. Black-Finish Pan Washer Head (Type A, Phillips Drive, Sharp Point) was one screw tested. These screws were #8 x 1.25 inch long. The screws cost $5.34 for a package of 50. The catalog description for these screws is:

> “These trim screws have a large washer-head surface that is ideal for attaching plastic and fabric. Heads are Phillips and recessed to resist tear-out. Black finish offers corrosion protection, improved lubricity, a decorative appearance, and a paint undercoat. Length is measured from under the head.”

The other screw tested was Oval Head Phillips with Countersunk Washer (Type A, Sharp Point). These were also #8 x 1.25 inch long. These screws cost slightly more at $13.48 for a package of 100. The catalog description for these screws is:

> “Also known as Sems trim screws, use these screws to simplify assembly, reduce small-parts handling, and provide a finished look. The washer is held under the head by rolled threads but is free to rotate, so when it touches the material the screw can still be tightened down. Head protrudes slightly above material surface. Length is measured from the top of the head. No. 6 and No. 8 washers have 1/2-inch outside diameter.”

In addition, fiberglass joint tape was placed at 45° around the openings. Three strips of tape, side by side, were installed at each opening corner, as shown in **Figure 14**. These strips were then covered with compound and painted. Likewise the screws were topped with compound and the final surface painted, however the design of the heads of the screws prevented a proper flat finish from being achieved.

**Fiber-Reinforced Wallboard**

The second innovative test, Test #13, was built with a different type of wallboard. This test was intended to represent a more expensive, but higher performing wall than Test #12. Industry suppliers suggest that the installed cost of this material is within 20% of standard gypsum
This was the only specimen tested in the project that did not use Standard 1/2-inch gypsum wallboard. FIBERROCK Brand Panels – Abuse Resistant wall material was provided by U. S. Gypsum to evaluate if the material would be resistant to damage. This material was developed to provide additional toughness for walls receiving high levels of abuse, such as may occur in the hallway of a school. We suspected that the toughness of the material would allow for it to remain intact at larger levels of drift than standard wallboard. U.S. Gypsum literature describes these panels as:

“…engineered to provide increased resistance to abrasion, indentation, and penetration for interior walls and ceilings in demanding construction applications. These gypsum fiber panels are designed to outperform paper-faced gypsum board. They are strong, solid, and durable, and resist denting, breaking, and puncturing.

The FiberRock material was heavier than standard wallboard (74 pounds per sheet as opposed to 62). This may result in increasing the mass of the structure and therefore altering the seismic behavior. Evaluation of the influence of this change in mass was beyond the scope of this project.

The wallboard was installed with standard wallboard screws. The supplier’s literature states that the typical screw withdrawal values for these panels is 95 pounds as opposed to 28 pounds for standard gypsum wallboard. Compounding and finishing were completed in the same method as for the other walls.

This specimen was noticed to have much poorer adherance between the tape and wallboard than the other tests. U.S. Gypsum recommends that SHEETROCK Brand Setting-Type Joint Compound or SHEETROCK Brand All Purpose Joint Compound be used for finishing joints. This proprietary compounding material was not used and may significantly improve the adhesion between the compound and tape.

**Repair and Retest Specimens**

Three tests (Tests #14, #15 and #16) were for walls built identically to previous specimens, originally tested to a limited peak displacement, then repaired, and then tested again. The loading protocol used for the testing was to test the original using the wall cyclic loading protocol up to the initial primary cycle at 0.6 $\Delta_M$. This primary cycle was completed and the wall was returned to a plumb condition. This drift level was usually above the peak force resistance for the walls. In addition, it was chosen as a point before the wallboard begins to loosen from the framing. It also was expected to be a level comparable with a damage loss between 50% and 100% of the replacement cost. The same maximum drift was used for all three walls even though the test variables were different, as shown in Table 6. This displacement control was kept constant to allow for direct comparison between the three tests.

After the initial loading, the walls were returned to a plumb position. The authors recommended the type and extent of the repairs of the damage. It was intended that the repair process replicate
a minimal level of repair, although the goal was to achieve comparable performance of the repaired wall. The repair methods used were based upon recommendations from wallboard suppliers (National Gypsum Company, 2001).

Specific repair methods used were:

1. **Fastener Heads**: The damaged wallboard pushed out from the head was removed, a new fastener was installed within two inches of the original fastener. The type of fastener (nail or screw) was the same as the original construction. Existing fasteners in the area of damage were not removed.

2. **Cracks at Wall Openings**: The paper of the damaged wallboard was trimmed back with a razor blade to expose the full width of damaged gypsum. This damaged gypsum was removed with a knife to expose the full depth of the crack. Compound was applied to fill the crack and then paper joint tape was installed over the compound.

3. **Large Cracks at Wall Perimeter**: The original paper tape was removed along with any loose compound or wallboard. New fasteners were installed within two inches of the original fastener. The same type of fastener (nail or screw) was used as was used in the original construction of the wall. Compound was applied to fill the crack and then paper tape was installed over the compound. New fasteners at the wall perimeter were only installed when it was evident that the existing fastener had failed.

4. **Minor Cracks**: Hairline cracks were filled with compound. No tape was installed.

After the repairs listed above were completed, the walls were finished with three layers of compound and two coats of paint, similar to the original wall construction process.

**Alterations to Original Construction**

After the first five tests it was quite apparent that the primary failure mode for the walls resulted in the fasteners being pulled through the back of the wallboard. Starting with Test #6, the fasteners were intentionally installed so that they would be either flush with the face of the wallboard or protruding a small amount. This protrusion limited the ability of the finishers to apply a smooth compounding surface and the paint crew to provide a smooth paint surface. The authors accepted this tolerance, as the quality of the wall finish was not an item of importance to the testing. However in actual application it was a concern that fasteners not be installed too deeply, especially when fasteners are placed 16 inches on center. The industry recommends no tolerance for installing fasteners. This appears to be impractical, as some tolerance is required for economical construction.

In general, very little splitting of the wood framing was seen during the testing. Reuse of the framing resulted in subsequent fasteners being installed near the location of previous fasteners.
Damage from the fastener to the framing was minimal, fasteners tended to stay firmly attached to the framing. After every third test, wood putty was used to fill the fastener holes from previous specimens to reduce the potential effect of reuse of a fastener hole. After several tests the authors determined that the integrity of the framing was beginning to drop, and the materials should be replaced to maintain the similarity of specimens. Almost the entire framing was replaced after Test #12. New studs were installed everywhere except for those framing the window opening. New king posts were placed at the doorway, and a new 4x4 post was placed at the end of the long pier. After Test #13 the window opening was removed and new framing studs were inserted into this area also. This would allow for all new materials for the last seven specimens (note the sequence of testing did not follow numerical order).

Sliding of the 4x4 post at the end of the long pier was a problem throughout the testing. The goal of the specimen design was to replicate the behavior of an interior wall that is surrounded by perpendicular wall surfaces. Sliding of this post was largely due to the artificial boundary conditions intended to model intersecting walls. In reality, the end stud would not be expected to resist this force, but rather the force would be applied to the intersecting walls. As shown in Figure 5, a 4x4 post was installed at both ends to support both the in-plane walls and the small portions of wallboard representing the intersecting wall. The post was originally installed with four 16d nails driven through the top and bottom plates. After Test #1, the post at the end of the long pier had slid approximately two inches along the length of the wall. After this test, a metal strap was placed around the base of the post and nailed to the bottom sill. This strap appeared to work suitably, except that a lateral movement of approximately 0.5 inch was required before the strap became engaged. During Test #13 the top plates slid laterally away from the 4x4 post at the end of the long pier. This appeared to be similar to the problems seen earlier when the bottom of the post slid badly. After removing the wallboard after the test the Simpson seismic ties were installed between the top plates and the post. Likewise during Test #8 similar damage occurred at the base of this post. In a similar fashion seismic straps were installed at the base of the post after Test #8. After Test #9, a steel angle was installed at the base of the vertical channel and held to the 2x foundation with three 5/8-inch lag screws. This prevented any horizontal sliding from occurring in the remaining tests.

Of the three styles of restraint: minimal, straps, and fixed, the one that accurately represents residential construction is difficult to discern. For upper level floors, where the restraint is provided by intersecting external walls, the restraint may be quite minimal. On the other hand, at the slab level where restraint will be provided via the attachment of the sill plate to the foundation, the horizontal restraint may be quite significant. The influence of this restraint on the damage levels was not deemed to be significant. Visible movement of the post usually occurred after initial damage states were achieved. In addition, this movement was usually visible after the peak load of the test had been achieved. This movement may allow for a cap on the magnitude of peak load and may reduce the post-peak strength of the wall.
Chapter 4. Experimental Test Results

Table 8 lists a summary of the data collected from the test program. Listed is the maximum force the wall resisted, in both total force and force per unit length, the maximum drift applied, the drift at the maximum load, and the total energy dissipated.

Damage Thresholds

Several damage thresholds were defined for the project. Some of the thresholds were defined before testing began and others were defined after specific patterns began to emerge in the first several tests. A damage event was the observation that the threshold had been achieved. The drift was recorded for each damage event. Visual means were used for the observation of each damage event, as instrumentation of such data would be impractical. Damage events were recorded and photographed while the transient drift was applied. It is expected that hairline cracking and local buckling often would disappear as the wall returned to a zero-load state. In a post-earthquake evaluation, these damage states may be difficult to observe.

The damage thresholds were:

1. Cracking of wallboard at a door or window opening, as shown in Figure 17. This was defined as the initiation of a hairline crack in the wallboard.

2. Cracking of paint over the fastener head, as shown in Figure 18. This threshold was defined as only when the paint was cracked over a single fastener. This did not include unsightly bulges formed by the fastener as it pulled itself though the backing paper of the wallboard. These bulges could become significant (more than 1/4 inch tall), especially at drift level over two percent. One reason for not including the bulges was the inability of the authors to establish definitive criteria for the event. In general, this bulging initially occurred at similar drift levels as when cracking was observed.

3. Cracking of the vertical joint at the perimeter of the wall, as shown in Figure 19. This crack forms between the in-plane wall of the specimen and the intersecting wall.

4. Local buckling of the wallboard in the vicinity of the re-entrant corner around the wall openings, as shown in Figure 20.

5. Cracking of the window opening when the vertical butt-joint of the front wall panels aligned with the re-entrant corner, as shown in Figure 21.

6. Cracking of the vertical butt-joint between panels, as shown in Figure 22. This included both tearing of the tape and relative slip between the tape and the wallboard.
7. Cracking of the tapered horizontal wall joint, as shown in Figure 23. This included both tearing of the tape and relative slip between the tape and the wallboard.

8. Crushing of the wallboard against the intersecting wall, the ceiling, or the foundation, as shown in Figure 24.

9. Wallboard extremely loose from the framing. This threshold was the most subjective of any defined. During testing it could be seen that the wallboard loosened appreciably from the face of the framing lumber. At extreme cases the wallboard was completely free of some of the fasteners and could be easily moved by hand. Repair of such panels would be difficult because installation of new fasteners would likely cause blow-out type failures at the location of the existing fastener. This threshold was achieved when the researchers could easily push the wallboard in or out from the framing a distance of about 1/2 inch.

10. Global buckling of a large portion of the panel, as shown in Figure 25. This threshold was defined as when a large portion of a panel buckled, usually with the loss of several fasteners. Global buckling is related to the gap at the base of the wallboard. Until this gap closes, buckling of a large portion of the pier is essentially impossible since the wallboard has little to react against. However, global buckling does not occur immediately after the closing of the gap, but gap closure is a necessary event before buckling. Global buckling may have been more prevalent if the orthogonal restraints had been built wider. During some tests, the panels were so free from the fasteners that the panels would slide out, and around the edge of the orthogonal restraint.

11. Loss of a portion of a panel, as shown in Figure 26. This damage threshold required that the panel be partially cracked through the gypsum panel, not completely along the original edges. It also required that the portion be completely detached from the framing fasteners.

12. Loss of an entire panel, as shown in Figure 27. This required the complete detachment of an entire panel from the framing. All edges were defined by the original factory-edge or field edge of the panel. This failure threshold has been documented in past earthquakes, although information about the maximum drift of the structure during the earthquake was not reported (Schmid, 1996, page 370). In this reported case, the wallboard was considered to provide lateral resistance for the structure and thus had fasteners spaced closely together. When fasteners are closely spaced, we believe that this failure mode is much more likely to occur, as discussed in the following section.
### Failure Modes

After observing the testing, there appeared to be two distinct modes of failure for the sheathing. The mode appears to be closely linked to the behavior of the taped joints. The first mode observed was rotation of large regions of the panels, often covering almost the entire pier. This mode occurred when the fasteners pulled through the backing paper of the wallboard, allowing the wallboard to slide over the fastener head. In this case the taped joints remained intact, usually though out the loading protocol. In fact upon removal of the panels after the test, the joint was often strong enough to maintain itself during demolition. In this failure mode the lower panels were seen to be the location where the visible damage concentrated. In fact portions of the upper panels were still very securely held to the framing at the end of the test. During the tests, 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.

The second failure mode resulted when the taped joints failed and allowed for relative slip between the panels. This failure mode was more similar to a racking behavior, where each panel rotated independently. This mode has been identified for plywood shear walls (Dolan and Madsen, 1992, pp. 420). Cracking of the paint over the fastener heads was usually seen to occur, but complete pull out of the fastener was much less likely. Often the two fasteners on different sides of the joint would cut grooves in the wallboard allowing the framing to slide relative to both panels, unlike the plywood walls reported where bending of the fasteners allowed for relative movement between sheathing and framing. Once again the damage of these walls was concentrated in the lower row of panels, but upon demolition, most fasteners were at least partially loosened from the wallboard. This failure mode appeared more prevalent when cyclic loading occurred, and was the dominant mode when the window opening was installed. In the case reported from the Northridge Earthquake, (Schmid, 1996, page 370) the wallboard was considered to provide lateral resistance for the structure and thus had fasteners spaced closely together. When fasteners are closely spaced, we believe that the second failure mode (racking of the panels) is much more likely to occur. This arrangement should place more load on the taped joints since significantly higher number of fastener heads are available to hold the wallboard to the framing.

### Monotonic Wall Behavior

The behavior of most walls was very similar. Table 9 lists the drift levels that various damage levels were observed for the monotonically loaded specimens.

1. Cracking at the door opening usually initiates around a drift of 0.25%. This crack slowly widens with increasing drift, reaching a width of 0.12 inch at drifts between 0.50 and 0.75% and 0.25 inch at drifts between 0.60 and 1%.

2. At approximately the same drift (between 0.25 and 0.75%), fastener heads begin to crack the compound and paint topping. Sometimes these initial fastener heads would occur at the perimeter and at other times they would occur in the field.
Surprisingly, several times it was seen that the edge fastener could completely tear out of the edge of the panel without ever damaging the surface finish.

3. The crack at the door opening grows significantly in length until a drift of approximately two percent was reached.

4. Maximum loads are resisted at a drift of approximately 1 to 1.5%.

5. For failure modes of pier rotation, the wallboard begins to move out-of-plane at the point of maximum load. The fastener heads pull through the back face of the wallboard panel.

6. For the joint failure mode, damage at the joints becomes prevalent and racking of the panels begins to occur.

7. As the drift increases to four percent the wallboard panels remain essentially undeformed but ride out over the top of the fastener heads.

8. After unloading the force, the wall returns to a significantly lower level of drift. Permanent drifts of approximately one percent were seen at the conclusion of a loading excursion.

Figures 28 to 35 show the relationship between the applied lateral load and the resulting drift for the eight monotonic tests. The behavior of all walls under monotonic loading appears similar, independent of the type and spacing of the fasteners. The failure begins with a small crack at the upper corner of the door opening. At much the same time the other upper corner of the door may buckle. This consistently occurred around a drift of 0.25% and this crack continues to grow throughout the loading. Fastener heads sometimes crack the paint over the top, but often pull out through the back of the wallboard without causing observable damage at the face of the wall. All walls exhibited some fasteners that broke the surface finish, but the number of fasteners that broke this finish could be a large or small percentage of the total fasteners that were detached from the wallboard at the end of the test.

At drifts of approximately 1% the maximum load was achieved, and the load resisted drops slowly as drift was increased to 4%. The crack at the doorway grows and additional cracking and crushing occur around the perimeter of the individual wallboard piers. Although not fastened directly to the framing at the top of the wall, the joint between the top of the wallboard and the ceiling wallboard does not become severely damaged. Figures 36 to 50 show photographs of the front face of each test at drift levels of 0.75 and 2%. These drift levels were chosen as they tend to bracket the drift levels where the peak load was resisted and the wallboard begins to separate from the framing.

Upon unloading and reloading in the opposite direction, little additional damage occurs, except for cracking at the upper corner of the doorway. Drifts in both directions, up to four percent are
resisted with loads approximately one quarter the maximum load resisted in the initial loading direction.

During demolition of the wall, the wallboard was almost completely free of most of the fastener heads. A few fastener heads remain strongly attached to the wallboard, usually in the upper corners of the piers.

**Influence of Tape and Compound**

The test specimens were taped and compounded to represent the actual construction of finished walls in typical homes. The finishing of this joint appears to influence the behavior of the piers significantly. The action that we saw occurring in the pier rotation failure mode was that the lower panel of the pier was almost completely free of the framing while the compounded joint resists enough load to hold the lower panel to the upper panel.

It was expected that the behavior would change if the wall were not taped and compounded. If this were the case then the upper and lower panels of each pier may behave independently. Horizontal, relative movement may occur between the panels and all walls would fail in the joint failure mode. The influence on the strength, stiffness and damage due to the tape and compound was difficult to assess without conducting tests specifically exploring this issue.

This may be a point to consider for other studies of the strength and stiffness of wallboard shear walls. The effect of the tape and compound may increase the strength and stiffness while resulting in independent failure modes of the panels. Unpublished reports of tested walls where the panels were not taped and compounded have shown that the failure mode of these walls is by racking of the panels and slip of the joints. These reports support the hypothesis that the tape and compound can significantly influence the behavior of the wall.

**Influence of Boundary Conditions**

The wall specimens were built with perimeter boundary conditions to represent the intersecting walls, the ceiling and the flooring that would usually surround an interior partition wall. Damage was often seen to occur at these perimeter locations although usually at drift levels that were significantly higher than the initial cracking at the door opening.

The primary influence of these boundary conditions appears to be due to the ability of the gypsum wallboard to react against these elements. The resistance provided by these elements allows a large force to be developed in the partition walls. Significant damage to the perimeter elements occurred in several of the tests, usually at the location of the end post of the long pier. Sliding of this post was seen in several tests, especially at the base. The force resisted by this post may have been significantly higher than would be seen by the end stud of a typical wall. This is due to the artificial boundary conditions that the end post was intended to simulate. However in most conditions, some element (most likely the intersecting walls) will provide this resistance. Anecdotal reports of exterior walls being pushed out of alignment were made after the 1994 Northridge earthquake. This type of damage was especially pronounced at the first floor of
multiunit, multi-level residential buildings. Also reported was the permanent movement of walls at doorways, resulting in the doorways being narrower than originally constructed.

**Cyclic Wall Behavior**

**Figure 13** shows the displacement control protocol used for the cyclic tests. This control displacement was based upon monotonic Test #5, as this specimen represents the most typical specimen configuration.

**Table 10** lists the drift levels observed for the various damage thresholds. The level of drifts where damage thresholds occur was comparable with the damage thresholds recorded for the monotonic loads. Three numbers are given for each damage level in **Table 10**. The first number is the drift that the damage threshold was observed. The second number is the maximum drift in the same direction that the wall had experienced when the damage threshold was identified, and the third number is the loading excursion number when the damage threshold was observed.

Initially it was expected that all of these damage thresholds would be observed during primary loading cycles. This assumption was based upon the belief that most damage would have a dominant factor of drift. By reviewing the table it was evident that several of the damage thresholds occurred in trailing cycles of loading. This would imply that some form of material degradation and memory exists.

**Figures 51 to 62** show the relationship between the applied lateral load and the resulting drift for the nine specimens loaded using the cyclic protocol. A total of twelve tests are included as three of the specimens were used in two different tests. Likewise, **Figures 63 to 86** show the photographs of the damage to the front face of the specimen at 0.75 and 2% drift.

The most common fastener damage was consistently a loss of hold on the wallboard. This resulted from the fastener head pulling through the paper facing, then punching shear through the gypsum, and finally tearing the backing paper. Sometimes this would appear in combination with bearing damage of the fastener causing a lateral cutting of the gypsum wallboard. Ridges could be seen in the face of the wallboard as a result of the fastener sliding behind the facing paper. Because the head of the fastener was able to laterally slit the facing paper, the head often made this ridge without cracking the latex paint. On a few rare occasions a fastener was seen to fail from fatigue due to bending. This was the case with a few screws and was observed during demolition of the test specimen. This rare occurrence was expected to be the result of poor quality control on the material properties of the screws. At the edge of the wall, fasteners were seen to fail due to edge conditions. Small portions of wallboard that were between the fastener and the edge of the wallboard panel were often able to resist only minimal force and often resulted in minor cracking of the gypsum.

**Aspects of Wall Behavior**

**Figures 87 to 90** are graphs of the relationship between the shear strain of the wallboard panels and the lateral drift of the test specimen. **Figure 87** is typical of the wall specimens that failed in
the pier rotation failure mode 1, pull-out of the fastener heads and sliding over the fasteners. These walls have almost no deformation of the wallboard, instead the entire assembly rotates as a rigid body. The other three graphs show specimens that failed due to tearing of the horizontal joints. These specimens show shear deformation of the pier, but this essentially is a result of relative sliding of the two sides of each joint. In addition, the relative deformation of the pier is still significantly less than the total applied drift. It should be noted that Test #10 and #13 are for specimens where an additional opening has been placed in the wall. This significantly reduces the length of the horizontal joint, thus weakening it to a point that it fails. The specimen for Test #17, in Figure 90, is identical to Test #5 except for the addition of trim pieces around the door and along the base. These trim pieces appeared to keep the fasteners from having pull-out failures. These trim pieces also assisted the specimen in resisting 1.19 times the maximum force of Test #5.

Figures 91 to 102 show the movement of the gypsum wallboard away from the framing. The figures are for six of the tests. Figures 91 to 96 represent typical wall behavior seen, while the other figures are for specimens with unique designs. The graphs compare the out-of-plane movement to both the applied force and the lateral drift. This out-of-plane movement has a large influence on the ability of the wall to be repaired rather than replaced. It appears that as the wall reaches its’ maximum strength, this splitting occurs. The potential improvement in wall performance appears to correlate with the ability to retain the wallboard tightly against the framing.

Figures 103 to 106 show the vertical movement of the door trimmer for four typical tests. One linear variable displacement transducer was placed on each trimmer to measure the vertical movement of the wall from the foundation. Both displacements have positive movement representing uplift. The graphs show a predictable effect that the door trimmer rises when the piers rotate. In general the upward movement was limited, although the movement can be as large as two inches, as seen in Figure 103. Downward movement was limited to a fraction of an inch, as downward movement causes bearing on the bottom sill and the foundation.

One aspect tested during the project was the influence of wall panel layout between the front wall and the back wall of each specimen. The front wall layout had a staggered panel layout, as shown in Figure 7. This pattern had a vertical butt-joint in the middle of the door header. As a result, the vertical joint at the window occurred at the upper left corner. The back wall had the vertical joint of both top and bottom row of panels in the middle of the wall. Overall, the location of this joint seemed to not influence the behavior, except when the joint was located at the corner of the window. In this case, the wall showed cracking along the direction of the joint, rather than inclined and passing through the panel. Another minor effect was the use of wallboard to cover a single bay of framing. When short wallboard panels were precut and attached to cover a single pair of studs, the panel would sometimes break loose from the wall, although this was seen to only occur at very high drift ratios. This seemed to be more problematic when the wallboard piece was originally cut to length, than in the case of the back wall where the piece was cut after the wallboard was hung. The damage to these short lengths may not be surprising, considering that all the fasteners are edge fasteners with no fasteners located in the field of the panel.
Of particular interest is the correlation of damage to that seen in actual earthquakes. From anecdotal information collected during the project, it would appear that the damage types seen during the testing are representative of that seen after a major earthquake, specifically cracking at re-entrant corners, joint failures, fastener head damage, and sluffing loss of portions of the wallboard. Industry comments report that the most common type of damage was cracking of the wallboard at re-entrant corners of doors and windows. Published literature on gypsum wallboard failures after earthquakes is limited in the available literature. Most photographic documentation of wallboard shows the walls in such severe states that it is difficult to determine the reasons for the damage.

In addition, we attempted to match the wall damage done as part of the shake table experiments of the full scale house to the damage done in this project. During the maximum shaking of the house peak drift ratios of 0.75% were obtained. After this level of shaking damage was observed at the base and upper corners of the door openings. However the damage was less severe than that seen for comparable drifts in this project. In addition, the cracking at the corners of the door openings was a collection of several smaller cracks, rather than a single long crack as seen in the testing of this project.

At the completion of each test, the wallboard was removed and a single cycle of drift was applied to the frame to measure the stiffness of the framing and anchor rod assemblies. Although not tested separately, it is believed that almost all the stiffness of this test is a result of the anchor rods. Figures 107 and 108 show typical graphs of these tests. The behavior can be seen to be almost elastic over the full travel of plus or minus four percent drift. The maximum loads resisted are about ten percent of the peak strength of the original test specimens. Table 11 lists the stiffness and correlation values for all of the bare frame tests.

**Comparison of Different Walls**

The design of the original test specimen matrix was derived to meet several test objectives. These objectives were:

1. Compare walls constructed identically to evaluate the repeatability of the test specimen.
2. Compare the behavior of walls built with different fasteners and at various spacings of fasteners.
3. Evaluate if there is a difference in the global behavior between walls loaded monotonically and those loaded cyclically.
4. Compare the change in behavior when the middle region of the wall is allowed to move vertically and when it is intended to be restrained. This objective was to simulate if a change in effect could be seen for walls built on the top story of a home and those built on stories supporting higher levels. It was expected that the weight of upper floors would counteract any uplift at the middle of the wall, hence forcing the wall to deform without vertical movement of the top.

5. Compare the performance of walls built using floating edge construction and those that are built with fasteners installed in the top plate.

6. Compare the change in behavior when a window opening is added to the wall.

7. Determine if the performance of the walls could be improved by using innovative construction techniques.

8. Determine the ability to reconstruct a damaged wall to a state that would perform similar to a new wall.

Comparison of Walls with Identical Construction

Test #3 was completed prematurely due to a loss of control on the actuator. This required an additional test specimen (Test #5) to be added to the total originally proposed. As a benefit though, it resulted in one set of tests where two specimens were built identically and loaded using the same protocol.

Figure 109 shows the force-drift relationship for the two walls. Until control was lost on Test #3 at a drift just under one percent, the two walls have similar strength and stiffness. This was especially true in the elastic region, under 4000 pounds load.

Comparison of Walls with Different Fasteners and Fastener Spacings

Figure 110 is a comparison of the three monotonic tests that had identical boundary conditions but different fasteners and fastener spacings. All walls had comparable initial stiffness. Test #1 with nails was significantly weaker at its’ maximum load than the other tests. Likewise Test #4 that had screws spaced at 8 inches on center was significantly stronger than the others. One aspect of interest on the wall with tighter screw spacing (Test #4) was the rapid loss of strength after the peak load was achieved. In fact, the drop in load resulted in a residual strength of approximately the same as the nailed specimen (Test #1).

Comparison of Monotonic and Cyclic Load Protocols

Figures 111 to 113 are the load-drift relationship for specimens that vary only in the two loading protocols. The monotonic behavior was very similar to the primary cycle of loading at each increment. However the trailing cycles are extremely lower than the load of the monotonic test at similar levels of drift.
Figure 112 is a plot for the tests that did not have the middle pair of anchor rods. Here the monotonic and cyclic tests are comparable in the region below drifts of one percent but begin to diverge after the peak load of the cyclic test was achieved. Figure 113 shows the same comparison as Figure 111 except the specimen has a window opening added. Once again the initial strength and stiffness of the two walls was very similar.

One behavior noted here was the non-symmetric behavior of the positive and negative cycles of loading. After considering possible reasons for this behavior, we suggest that the reason was likely due to the boundary conditions of the long pier. Whereas the positive excursion of loading the base of the pier was pushed against the intersecting wall assembly, the negative excursion causes the base of the pier to move into the doorway with minimal reaction. While this behavior was especially obvious in the tests with the middle pair of anchor rods, it did occur in all tests, but with a less pronounced effect.

Comparison of Vertical Flexibility in the Middle of the Wall

Figures 114 and 115 are the load-drift relationship for specimens where the middle pair of anchor rods may or may not be installed in the testing frame. Initial stiffness of the specimens was much the same, but the peak load resisted was significantly different. The allowance for vertical movement of the middle portion of the wall allowed both piers to roll about the end of the pier. Although the peak strength of the wall without the middle pair of anchor rods (Test #2 and #7) was lower, it also occurred at a much higher drift and maintained its’ strength for most of the test.

This same affect can be seen in the uplift measured at the door trimmers. Figure 103 shows a large vertical displacement of the trimmer at the large pier. This was a result of the removal of the anchor rod at the middle of the wall. The vertical movement remains negligible until the load begins to approach the maximum resisted. In addition, the lack of vertical restraint allows the door trimmer of the short pier to also rise. This was the opposite of the expected result that the piers rotate independently. The effect of this vertical restraint was particularly noticeable when compared to Figure 104, the identical wall with the middle anchor rod installed.

Test #2 showed much earlier damage thresholds than many comparable tests, and the extent of damage appeared to cover the wall surface faster. Since this test was intended to simulate the upper floor of a two-story home, this appears to contradict the commonly seen damage after earthquakes where the upper levels are less damaged than the lower levels. One explanation for this discrepancy may be that the lightweight roof of a building does not generate the forces necessary to develop the drifts required to produce the damage.

Comparison of Wall Openings

The placement of a window in the wall significantly affects the peak load as shown in Figures 116 and 117. These figures show that while the peak load was reduced, the residual strength, initial stiffness, and strength at low drifts are essentially the same with or without the window opening. Test #10 had a total load that was 68% of the strength of the comparable Test #5, as seen in Figure 116. This ratio is 88% when calculated as the strength per unit length of wall without
openings. Thus the assumption that wall strength is a linear function of the total length of individual piers is inaccurate, but not completely without basis. Recent recommendations developed for plywood shear walls may provide more accurate predictions of wall strength based upon the unit sheathing strength (Ni et al., 1999).

Under cyclic load protocol, as shown in Figure 117, once again the peak load was significantly less and also the addition of the window reduces the residual strength. Here the peak load was 64% of the wall without a window opening (Test #11 and Test #6). The ratio of the unit strength of wall was 83%.

**Comparison of Floating Edge vs. Typical Construction**

The majority of the test specimens were built using floating edge construction, i.e. no fasteners located in the top several inches of the wall. This was the norm for the wall specimens tested because of the recommendations of the gypsum industry for the past twenty years (see publication GA-216-96 Section 4.9.2.1). The 1997 Uniform Building Code also permits this style of construction in Section 2511.3. It does not appear to be common practice, in Northern or Southern California, although a few people have mentioned that they have seen walls built this way.

In reality, little damage occurs at the top joint of the panels. It would appear that installing this fastener at the top does not influence the strength, stiffness or damage of the specimen. A comparison of the wall strength of Test #8 to Test #1 and Test #9 to Test #5 shows a strength ratio of 136% and 129%. In the author’s opinion, attributing this much change in strength solely to the placement of these fasteners in the top plate is inappropriate. Closer spaced fasteners, as for shear wall construction, were beyond the scope of this project; based on the performance of the tested walls, it is the author’s opinion that additional fasteners in this location would have minimal impact on the wall performance.

**Comparison of Beneficial Effects for Innovative Systems**

Comparison of the damage levels for the innovative systems and the control system showed that both innovative systems reduced the level of damage. Table 10 shows that all the systems reached the various damage thresholds at comparable drifts. However, both innovative systems appeared to slow the propagation of the crack at the door opening significantly. In addition, both innovative systems appeared to delay the ability of the fasteners to pull through the back of the wallboard. This reduced the “looseness” of the wallboard and thus should allow for repair to be economical at higher levels of drift. Returning to the damage patterns shown in Figures 67 through 72 the extent of cracking appears to be reduced. Figure 118 shows a close-up view of the cracking at the door opening for 0.75% drift for Test #11 and #12. The growth of the crack appears to have been retarded by the application of the fiberglass tape. Likewise Figure 119 shows the relative performance of the crack for all three tests.

By comparing Test #12 and Test #13 to Test #11 the change in strength of these two innovations can be seen. Test #11 was an identical specimen built with conventional methods. Test #12
resisted 121% of the control specimen and Test #13 resisted 149%. It should be reiterated that the goal of these innovations was not to increase the strength of the wall, but to reduce the damage. Although the tested innovations did result in significant increases in the strength, the authors believe that other means should be employed when higher strengths are desired.

**Influence of Door Frame and Baseboard**

Test #17 was built to consider the influence of the door frame and baseboard to the performance of the gypsum wallboard system. The maximum force resisted was high compared to similar specimens as shown in Table 8. This test behaved in the second (joint failure) mode, with failure of the horizontal and vertical joints allowing for relative slip between wallboard panels. This may very likely have been due to the ability of the baseboard to keep the wallboard closely attached to the wood framing. The wallboard at the edge of the pier remained close to the framing throughout the full range of loading as shown in Figures 101 and 102. A comparison of the damage thresholds for this and the other walls in Table 10 shows that the failure of the vertical joint, and especially the horizontal joint, occurred earlier than the average wall. Likewise comparing the values in the table shows that the paint cracked over the fastener heads at much higher drifts than other tests. In addition, throughout the test the number and distribution of fastener damage was significantly reduced. Even though the strength and stiffness of the baseboard used for the testing was minimal, this additional restraint on the wallboard did seem to govern the failure mode that occurred.
Chapter 5. Damage-Cost Relationship

The economic loss of structures is a concern when developing performance based engineering decisions. Milne (1939, page 50) provides a very early estimate for the Expected Loss Ratio of woodframe residential structures to be in the range of 20-30% of the sound value of the residence. He determined this damage amount to be expected for the average structures in the vicinity of a great earthquake. His original estimates are based upon period construction, plaster and lath finish rather than wallboard. Since that time, the Applied Technology Council, as well as others, have conducted additional studies on economic damage.

Fragility Curves of Individual Damage Thresholds

During testing, data was collected relating certain damage thresholds to lateral drift. This recorded drift level may vary for the front and back wall of each specimen. With a total of 17 specimens, and with three of them retested, this results in up to 40 values of drift for initiation of a given damage threshold. Fragility curves were plotted for the dominant damage thresholds, including:

1. Cracking of the re-entrant corner at one of the wall openings.
2. Loss of compound or cracking of paint at one fastener head.
3. Cracking of the taped vertical joint to one of the intersecting walls.
4. Local buckling of the panels at one of the re-entrant corner of one of the wall openings.
5. Cracking, tearing or slipping of the joint compound at one of the vertical butt-joints.
6. Cracking, tearing or slipping of the joint compound at one of the horizontal wall joints.
7. Crushing of wallboard panels somewhere along the perimeter of the wall.
8. Buckling of large regions of the wallboard panels.

Crack widths were not specifically monitored during testing. Hairline cracks were usually seen to occur. These cracks would grow in both length and width as higher drift ratios were applied, as was discussed in the earlier discussion about the behavior of walls loaded using the monotonic protocol.

Fragility curves were plotted for each of the damage thresholds for three different populations of wall tests. The first population was for all tests where the damage threshold event was recorded, or was identified at the end of the test of not having occurred. This population represents the wide variety of wall constructions and boundary conditions tested. It also includes the innovative systems and the damage and repair specimens. This population had a maximum size of 40. The second population was for monotonic tests with typical construction methods (Test #1, #2, #3,
This subset had a maximum size of 16. The third population was for tests using the cyclic protocol (#6, #7 and #11), had a maximum size of six, and specifically did not include tests that had either innovative systems or repair specimens.

For each damage threshold and each population, the recorded drift level for the event to occur was ranked in increasing order. This data was obtained from Tables 9 and 10. For cyclically loaded specimens the maximum drift achieved in a previous primary cycle was used in the case where the event occurred in a trailing cycle. Each event was then plotted on the fragility curve as a point with the coordinates of the drift of the event and the number of tests that had recorded the event by the drift shown divided by the total size of the population.

Figure 120 shows the fragility curve for cracking at the re-entrant corner of the wall opening. Almost every test has reached this event by a drift of approximately 0.5%. The highest drift event was for Test #12, one of the innovative systems. The second highest event was for Test #1, the wall with nails at eight inches on center.

Figure 121 is the fragility curve for cracking of the paint over the fastener head. It should be noted that this represents the case of a single fastener head being damaged somewhere in the wall. While almost 80% of these events occurred before a drift of 1%, they all occurred before 2% drifts were applied. This graph also shows that while the monotonic tests form an upper bound on the damage threshold, the cyclic tests form a lower bound. This trend was seen in almost every damage threshold. For this damage threshold, Test #17 recorded the highest drift.

In Figure 122, for failure of the vertical joint to the intersecting wall, we begin to see damage thresholds that are not achieved in every test. This graph also shows a significant step at a probability just under 60% and a distinctly nonlinear behavior at higher drifts.

Likewise in Figure 123, for local buckling at the wall opening, the behavior becomes nonlinear for the higher drift events. Here, as in Figure 120, the difference between the three populations is insignificant.

Figure 124 is for failure of the vertical butt-joint and Figure 125 is failure of the horizontal joint. Both of these damage thresholds occur only with the second mode of failure discussed earlier (racking of the panels). The data for the vertical joints indicates that this threshold is much more likely in the cyclically loaded wall specimens, in fact it only occurs in about 50% of the monotonically loaded specimens. As seen in the second figure, the occurrence of failure of the horizontal joint is much lower. Two reasons are given for this disparity. First, the taper of the horizontal joint allows for more compound to be applied and to be more evenly distributed. Second, the vertical joint is partially in the lower half of the wall, the location where most of the damage occurs.

Figure 126 shows the occurrence of crushing at the perimeter of the wall. This is the one threshold where the monotonically loaded specimens consistently fail before the cyclically loaded.
The primary reason for this change is the higher likelihood of this occurring when the panels rotate as a unit, rather than fail the joints and rack.

Figure 127 is for global buckling of the wallboard. Since the loading protocol for the damage portion of the damage and retest specimens was stopped before any wall experienced this event, the population for the All Test graph was reduced to 34. Global buckling was seen to occur in only about half the wall specimens. However it should be noted that this event would most likely have been seen more often if the bottom foundation had been wider (see Figure 8). It is expected that this failure mode will eventually occur in any wall specimen that allows for excessive rotation to occur, resulting in the panel bearing on some orthogonal element. Both crushing at the perimeter wall and global buckling are expected to be dependent upon the pre-earthquake gap between the wallboard and flooring.

Estimation Process

Licensed contractors in California evaluated the level of damage. The tests specifically evaluated were Test #1, Test #2, Test #5 and Test#6. These walls were chosen to compare different loading protocols, vertical stiffnesses, and different fastener types. The walls were to represent an appropriate sample of typical applications in the housing industry. Although the damage thresholds occur at different levels for walls constructed using different construction details, as shown in Tables 9 and 10, it is probably inappropriate to make recommendations about specific recommended practices based solely on the data collected in this testing program. Table 12 contains a list of the contractors and a brief description of their qualifications.

Each contractor was shown a collection of photographs that documented the visible damage that the wall contained at various levels of drift. These photos gave both a global view and local detail views of the different levels of damage. Photographs were taken of the front face of the wall while it was fully displaced to the drift level. During cyclic testing it became apparent that when unloaded to a zero-force condition, the drift reduces significantly. One goal of the monotonic testing was to determine the loading protocol for the cyclic tests. Unloading of the specimen, particularly after reaching the maximum load, could result in altering the post-peak behavior. Thus it was concluded not to unload the specimen to zero-force at each level of drift. The estimators were asked to use their best judgment when determining the repairs required for a zero-force condition resulting from the photos taken at the maximum applied drift. This relaxation of the wall drift results in cracks becoming significantly narrower and possibly reducing their likelihood of requiring repair (because they are undetected) or the extent or difficulty of repairs (because they are narrower and finer).

The contractors were told that the wall represented the average level of damage in an average three-bedroom, 1600 sq. ft. tract home. Because cost of repair includes fixed costs of transportation, set-up and clean-up, the estimators were told to assume that all walls in the home showed similar damage levels. Another assumption was that there would be approximately ten doorways in the entire structure. It was also expected that the homeowner would represent a typical homeowner, in relation to their expectations of repair and acceptability of the quality of
construction. The cost was not to include the cost of returning the structure to a plumb position; this cost was assigned to structural failure of the lateral system. The costs were estimated for a double-sided, interior partition wall with gypsum wallboard on both faces. Once the level of damage exceeded the value of replacing the wall, the estimators were told to skip higher levels of damage of the same wall specimen.

The contractors were asked to determine the type of repair work recommended, the estimated cost of repairing the damage, and the cost of replacing the wall completely. The cost estimates were converted to a Damage Cost Ratio (DCR) by dividing the repair cost by the replacement cost. **Figures 128 to 130** show the DCR values determined from the various estimators. **Table 13** lists the repair procedures recommended by the various contractors.

Several factors affect the actual cost of repairing damage. These include:

1. geographic location
2. local and regional construction markets and competitiveness
3. homeowner’s personal tastes and acceptance levels
4. wall finish and texturing design
5. ability to match paint color for touch-up work
6. size of home and repair job
7. amount of time required for set-up and clean-up

No specific means were made to evaluate the influence of individual factors. It was assumed that the DCR would be relatively independent of several of these factors, as the cost of repair should fluctuate similar to the cost of replacement or reconstruction.

The influence of permanent lateral movement of the wall on the economic loss of the structure is difficult to quantify. For this project it is expected that the structure has returned to a plumb position by some means other than the work performed to repair the wall finish. Anecdotal information from industry indicates that a structure with visible, permanent lateral movement will have all finish materials removed during the process of replumbing the structure. For this project, that cost is expected to be incurred by failure of the lateral structural system rather than the nonstructural elements.
Another factor not considered in the estimates was the cost of repainting a large area of a home due to a few cracks in one or two walls. Estimators were told to consider that all walls in a home were damaged equally; hence repair and repainting of one wall would not incur the cost of repainting other walls. According to the 1997 California Fair Claims Settlement Practice Title 10, Section 2695.9 a.2:

“When a loss requires replacement of items and the replaced items do not match in quality, color or size, the insurer shall replace all items in the damaged area so as to conform to a reasonably uniform appearance.”

This regulation has traditionally been interpreted to mean that if one portion of a room needs to be repainted, then the entire room is to be repainted to allow for the paint color to match correctly. This regulation replaced previous wording that used “line-of-sight” as the criteria for the extent of required painting. The regulation is mandated in the state of California, which tends to have more stringent insurance requirements than most of the United States. In other regions of the country, comparable insurance requirements are sometimes, but often not, as stringent.

Comments Received from Estimators

Informal discussions with the estimators provided insight into how the cost of repair may be determined by different contractors. Method A would be when a general contractor hires a variety of sub-contractors to perform the different types of work. For this method, the DCR values are similar to a step function. The cost of repair is quite low as long as the level of repair work involves a general contractor who can patch and paint the small cracks. When the level of damage becomes significant enough to require a paint crew to paint the entire wall, the DCR value jumps significantly. At much the same level of damage, a full drywall crew is required to begin taping and patching cracks. After this initial jump, the DCR grows gradually as the drywall crew is required to fix more extensive damage. This method incurs fixed costs every time that an additional subcontractor is required. However, the specialization of trades results in workers with high skill (carpentry, painting) and low skill (demolition) and comparable changes in compensation.

Method B of estimating represents a different business structure. This method was used by one of the contractors whose intent is to have a single company perform all repair work. In this structure, the employees require multiple work skills, thus qualifying for increased compensation. The estimates that come from this type of company usually start with a significant initial cost for any level of repair. However, after the initial cost, the incremental costs are less dramatic as they represent additional labor but not additional fixed costs.

One estimator considered that a carpenter might be required to adjust the doorway if the wall opening is badly damaged. He expected this adjustment to the door frame to be required at a transient drift of 0.75%. His estimate was based on the point where a common door frame would rack to a point where the door would stick. In Test #17, an actual door frame was installed, unfortunately the test frame design did not allow for the inclusion of an actual door during testing.
The test did appear to show that the jamb and frame become quite loose during lateral movement, possibly allowing a door to operate at drift ratios far above 0.75%. This looseness will allow for the door to operate, but would most likely require repair after the earthquake. Industry personnel suggest that a permanent lateral drift ratio of 0.25% will result in doors “sticking” and requiring repair.

As small regions of the wallboard are badly damaged, for example at the openings, small portions of the panels need to be removed and replaced. This requires an additional cost for demolition and disposal. Complete loss usually occurs when large portions of the wallboard must be replaced.

A key factor in the repairability of the wall is the loss of connection between the wallboard and the framing. Once the wallboard becomes loose from the wall, the repair becomes significantly more difficult. Remounting the wallboard against the framing requires installing new fasteners. To return the wallboard to a flush condition is difficult because of the damaged fastener that remains behind the wallboard. When new fasteners are installed, these dislodged fasteners often cause a puncture to the wallboard. These punctures may be a few inches in diameter and often require significant amounts of compounding and rebuilding. Because of this labor-intensive work, the cost of repair becomes much higher than replacement with new wallboard. Photographic documentation of the “softness” of the wallboard was impossible to obtain. Instead estimates of this damage level were based upon the observed behavior and the judgement of the principle investigators. Recorded data was also used for the basis of this judgement, such as the splitting of the wall shown in Figures 91 to 102.

The mode of failure may contribute to cost of repair, but this is beyond the scope of this limited study. One factor in this decision would be the ability to reuse the wallboard. When the second mode of failure (the racking mode) occurs, the wallboard itself receives less damage, instead the damage concentrates in the taped joints. The relative cost of repairing taped joints versus reattaching the wallboard with new fasteners may be an area for more in-depth study.

**Prediction of Cost as Related to Drift Ratio**

Two methods were used to analyze the repair estimates obtained from the estimators. The first was to determine the fragility curves defining different states of economic loss. Four damage states were defined: 25% loss, 50% loss, 75% loss and 100% loss. Linear interpolation was used to determine the drift that would result in each of the first three damage states for each of the four tests for each estimator. This resulted in a total of 12 values for each damage state. Fragility curves were plotted for each damage state. Each fragility curve was then fit with a logarithmic function, as shown in Figure 131.
For the 25% damage state, the fragility curve was modeled, with correlation $R^2$ of 0.9627, as:

$$Y = 0.609 \ln(X) + 1.02$$  \hspace{1cm} \text{Eq. 1}

For the 50% damage state, the fragility curve was modeled, with correlation $R^2$ of 0.9489, as:

$$Y = 0.705 \ln(X) + 0.453$$  \hspace{1cm} \text{Eq. 2}

For the 75% damage state, the fragility curve was modeled, with correlation $R^2$ of 0.9171, as:

$$Y = 1.234 \ln(X) + 0.032$$  \hspace{1cm} \text{Eq. 3}

For the 100% damage state, the fragility curve was modeled, with correlation $R^2$ of 0.8919, as:

$$Y = 1.558 \ln(X) – 0.367$$  \hspace{1cm} \text{Eq. 4}

The second method used for analyzing the data was to curve fit the data of DCR to drift. This value can be converted to dollar values of loss by multiplying by the expected replacement cost of the wall under consideration. Thus,

$$\text{Loss} = \text{DCR} \times (\text{Replacement Cost})$$  \hspace{1cm} \text{Eq. 5}

For this graph, three different models were considered: linear, polynomial and logarithmic to predict the DCR as a function of the drift, in percent. For this evaluation, all DCR values obtained from the estimators were used, up to the level that the DCR was equal to 1.0. Higher values of drift for a specimen after the evaluator’s DCR had reached a value of 1.0 were ignored. The authors’ opinion is that the values ignored would have biased the resulting regression. A total of 134 points were used in the regression, as shown in Figure 132.

The linear model had a correlation $R^2$ of 0.6897 and an equation of:

$$\text{DCR} = 0.452 \times (\text{Drift}) – 0.001$$  \hspace{1cm} \text{Eq. 6}

The polynomial model had a correlation $R^2$ of 0.6963 whether a cubic or fifth order polynomial was used. The cubic equation was:

$$\text{DCR} = -0.029(\text{Drift})^3 + 0.044(\text{Drift})^2 + 0.448(\text{Drift}) – 0.037$$  \hspace{1cm} \text{Eq. 7}

The logarithmic model had a correlation $R^2$ of 0.6523 and an equation of:

$$\text{DCR} = 0.374 \ln(\text{Drift}) + 0.524$$  \hspace{1cm} \text{Eq. 8}

All of these three equations have comparable correlation with the data. The logarithmic regression is recommended because it represents better the expectation that small levels of drift can be resisted without the occurrence of economic damage. If the simpler linear value is preferred, it also can give accurate results, particularly at higher drift levels.
Another item of interest was to consider the relationship between the maximum transient drift of a wall during an excursion of loading to the residual drift when the load is removed. Test #6 was reviewed for this information. This test was for cyclic loading and was constructed the same as the standard test specimen, Test #5. For each loading excursion, both positive and negative directions, the residual drift of the specimen was plotted as a function of the maximum transient drift of the excursion. The data for the zero-load point was selected as the point with the lowest absolute force at the end of each excursion. Figure 133 shows these points and the linear regression through zero-intercept of the points. The regression shows that the residual drift is approximately 16% of the maximum drift of the excursion. The regression is based upon all excursions of the test, without weighting of those excursions with larger drift. As the graph shows, the correlation is quite good, especially for the positive direction of loading. In addition, the regression very closely fits the extremes of the transient drift data in both the positive and negative directions. The photographs in Figures 134 to 137 show the change in the visible cracking when the wall is held at maximum displacement and after the load is released and the wall returns to equilibrium. All four photographs are of the last test specimen, Test #17. Figures 134 and 135 were taken for a primary cycle with a maximum transient drift of 1%, while Figures 136 and 137 are for a primary cycle with a maximum transient drift of 2%. As the photos show, the cracks close significantly when load is removed, however repair of the cracks are expected to be much the same since the crack length seems to be more closely related to repair costs.
Chapter 6. Conclusions and Recommendations

Conclusions

After reviewing the test specimens, the behavior and the photographic documentation, the authors have made the following conclusions for the original research objectives:

1. The cost of economic damage to a gypsum wallboard system can be predicted by multiplying the cost of removing and replacing the wallboard by the DCR. The logarithmic predictor for the DCR is determined from Equation 8.

2. Both screws and nails give acceptable performance for wallboard systems. Although it is often believed that screws hold the wallboard tighter to the framing, benefits of this were not seen to be significant. Decreasing the spacing of screws significantly increased the strength of the wall, but also resulted in more significant loss of strength after the peak load was achieved.

3. Monotonic load protocols accurately predict the backbone curve traced by the primary cycles of the cyclic loading protocol. Damage states are comparable for monotonic and cyclic loads, but monotonic loading places an upper bound on the drift that a wall can withstand without an event occurring.

4. Very little change was seen in the behavior of the walls due to the use of floating edge construction versus fastening of the wallboard to the top plate.

5. 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 wall than any other parameter studied, except the addition of more wall openings. Rolling movement, as in Test #2, tended to initiate damage at lower levels of drift, as seen in Tables 9 and 10. In addition, the DCR in Figures 128 to 130 tended to be higher for this behavior. This rolling is expected to occur in upper floors where damage seen in past earthquakes has been significantly less than lower floors. This appears to contradict the findings of this project. However, the authors propose that more extensive analysis of residential structure will show that upper floors receive lower levels of interstory drift due to the lighter masses they are required to support. If so, this reduced demand in drift, corresponding to lower levels of damage, will be consistent with this project's findings.

6. The influence of an additional opening resulted in multiple changes. First, it changed the long pier to two narrow ones. This change shortened the length of the horizontal taped joint and is believed to have changed the mode of failure. In addition, the second wall opening resulted in three times the number of re-entrant
corners in the walls, causing multiple crack initiation sites. On the other hand, the wallboard on walls with added openings remained tighter against the framing, possibly delaying the point where the entire face of wallboard would be required to be removed and replaced.

7. The only detrimental affect seen from the placement of vertical joints was when the joint aligned with the re-entrant corner of an opening. This resulted in an early initiation of slip of the joint. The drywall industry has previously recommended that this practice be avoided and the research conducted here supports that recommendation.

8. 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.

9. Minimal repair methods tested for this project resulted in walls that resisted between 0.803 and 1.235 times the load of the walls before the original damage. It should be noted that the one repaired wall that resisted more load than the corresponding undamaged wall, did so at a drift level significantly higher than the initial test had been deformed. Damage thresholds that were reached in the undamaged initial test, occurred at lower drift levels in the repaired wall. Damage thresholds that did not occur in the initial test, appear to have occurred at drift levels comparable with those that the original wall would have achieved.

**Static vs. Dynamic Failure Patterns**

The test protocol was for static loading, with a monotonic test taking approximately two hours to reach four percent drift. From the appearance of the damage, the results look similar to what one might see after a home experiences a slow settlement due to soil consolidation. Test #3 was ended abruptly when the control system malfunctioned. What resulted was a rapid movement in the opposite direction of the original loading. Although similar to the damage seen in the other tests, the cracking pattern observed was more dynamic and showed signs of impact. This dynamic damage included cracks branching off from the main crack, crack growth in more erratic directions, and more pronounced tearing of the paper and grinding of the faces of the cracks.

One recommendation for future research is that the rate of loading be increased to represent actual seismic motion. These tests would be conducted at specific peak drifts, allowing for photography of the damage to be correlated to the drift. In addition, documentation of the damage state incurred at a specific drift would be recorded at a zero-force condition, rather than the deformed state that this project utilized.
Revision of Control Displacement for Cyclic Loading

The control displacement for the cyclic loading protocol was based upon 0.6 times the displacement where resisted load was 80% of the peak load. This point of 80% of peak load was around two percent drift, placing the 0.6 value to be near 1.2%. However, perhaps this control displacement should be based upon the force resisting system of the structure. This leads to an unresolved question. Since the testing conducted for this project was for architectural features, should the displacement control used be determined from the peak strength of the wall finish, or rather, obtained from the testing of the building’s structural shear walls?

Recommendations

The following items may be considered when using the information included in this report.

1. Engineering strength parameters from building code provisions are significantly less than values from published experimental data. This was also confirmed by the testing for this experimental program. Even when applying common factors of safety to allowable design strengths, the building codes are well below the actual wall strengths.

2. Previous published testing of wallboard systems is available on a limited basis to attempt to quantify the engineering parameters of strength and stiffness. However results have varied significantly and the population of tests has been small.

3. While engineered shearwall systems seem to be well defined, the detailing of conventional construction has been limited in publication. As a result, the survey results showed a wide variation in the specific construction practices used today.

4. Minor damage begins to occur at drift levels of 0.25%, although limited to hairline cracking at wall openings. Significant increases in this damage appear at drifts of approximately 0.75%. After drift levels of 2%, the additional damage is limited to major damage levels such as global buckling or loss of portions of the wallboard.

5. The maximum strength of walls usually occurs in a range of drift ratios between 0.75% and 1.25%. The walls that had peak loads at higher drift levels than this range, were almost exclusively limited to those that represented walls with lower gravity load and limited resistance to vertical movement. In those cases, the peak load occurred much later, but with minimal increase in the load achieved at 1% drift.
6. Two exclusive modes of failure were seen in the test specimens. When taped joints have significant strength, the wallboard was seen to pull off the fastener heads and then slide over the intact fasteners. In the other mode of failure, the taped joints and compound failed and allowed relative slip to occur between wallboard panels. In this case, the panels racked individually. Fasteners almost exclusively failed by either pullout or tearing through the edge of the panel. Rarely, but occasionally, were fasteners found to fail due to bending. Withdrawal of the fasteners from the framing was not observed in any of the tests.

7. Damage to fastener heads and relative movement between the framing and wallboard was seen to occur in the lower half of the walls. By the end of testing the lower half of the wall was completely released from the wallboard while the upper half was often still strongly attached to the framing.

8. The existence of intersecting walls and ceilings results in significant damage, such as the crushing of wallboard against these orthogonal elements.

9. Incremental and initial cost estimates vary depending upon the business plan of the estimator. Two methods were seen in the estimates obtained. One represented a general contractor expecting to hire subcontractors to perform the majority of work. This method resulted in a step function based upon the number of trades required to repair the wall. The second method was for a contractor who performs all the required work. In this method initial costs are high, but incremental costs changed less dramatically.

10. Damage, especially minor cracking, may be very difficult to accurately estimate. In this project, the influence on cost of adjoining walls beyond the one tested was not considered. When considering the cost of adjoining walls, it is expected that repair costs will follow a marginal process. Common insurance practice is to repaint all walls in a room with a single damaged wall. Hence, the first crack in a room requires painting of the entire room, whereas the same crack in a different wall of the room does not require the same repair cost, as the cost of repainting this second wall has already been paid. One potential method of improving the cost-damage model would be the use of model homes. These homes would be defined to have a certain level of damage, and a clearly defined scope of work for the contractor to complete. These case studies could then be evaluated for the cost of repair. One drawback to this method may be trying to extrapolate the cost-damage model to structural configurations different from the model homes.

11. Damage can be delayed to higher levels of drift by changing the materials used or the installation technique. Reinforcement at the wall openings slowed the extent of cracking up to drift levels of 0.75%. Large headed fasteners held the wallboard tighter against the framing. Wallboard made from different materials was more
durable, and showed less degree of damage at comparable drift levels. These improvements in performance were limited, but significant.

12. Minimal repair methods tested in this project approached but did not exceed the performance of the initial undamaged wall. Once drift levels above the level repaired were applied, the repaired wall appeared to perform the same as it would have initially.

13. Testing to evaluate the esthetic performance of building assemblies should be performed on specimens of complete construction. For this test series, the taping, compounding and painting was a significant investment of resources. However, this resulted in an ability to accurately determine when damage events would result in visible damage.

14. Comments from construction personnel indicate that the guidelines published in codes and industry standards are often not followed in practice. Fastener spacing is often much smaller than the maximums allowed, and vary significantly from one contractor to another. One reason for this practice is so that all walls of a project use the same spacing, thus eliminating the potential confusion of the workers.

15. Drift levels recorded in this test series do not include the effects of dynamic, short-term loading. The result may be closer to the damage state incurred due to slower building movement, such as settlement. One recommendation is to conduct an additional series of tests at higher frequency of constant, maximum displacement damage cycles. These tests may provide better correlation with damage incurred during real-time shake table tests.

16. It would be tempting to recommend specific detailing choices as a means to reduce the expected damage in future earthquakes. The data indicates changes in the drift where damage thresholds occur, and that these changes are a result of alternative construction details and housing designs. However, such detailed recommendations are probably not warranted based upon the small sample size of walls tested and the repeatability of the tests.
References


### Table 1: Wall Tests Reviewed from Literature

<table>
<thead>
<tr>
<th>TEST</th>
<th>SHEATHING</th>
<th>ATTACHMENT OF WALLBOARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>APA 25</td>
<td>1/2&quot; Gypsum board on Side 1, 5/16&quot; Structural I plywood on Side 2</td>
<td>Nails 7 inches on center</td>
</tr>
<tr>
<td>APA 26</td>
<td>1/2&quot; Gypsum wallboard on Side 1, Side 2 unsheathed</td>
<td>Nails 7 inches on center</td>
</tr>
<tr>
<td>APA 27</td>
<td>1/2&quot; Gypsum wallboard covered with 3/8” Group 4 (Cedar) Channel groove plywood on Side 1, Side 2 unsheathed.</td>
<td>8d galvanized casing nails at 4” on center at edge and 12” on center in the field</td>
</tr>
<tr>
<td>APA 28</td>
<td>1/2” Gypsum wallboard covered with 3/8” Group 4 (Cedar) siding on Side 1, Side 2 unsheathed.</td>
<td>8d galvanized casing nails at 4” on center at edge and 12” on center in the field</td>
</tr>
<tr>
<td>APA 29</td>
<td>1/2” Gypsum wallboard covered with 3/8” Group 4 (Cedar) Channel groove plywood on Side 1, Side 2 unsheathed.</td>
<td>8d galvanized casing nails at 6” on center at edge and 12” on center in the field</td>
</tr>
<tr>
<td>APA 30</td>
<td>1/2” Gypsum wallboard covered with 3/8” Structural I plywood on Side 1, Side 2 unsheathed.</td>
<td>10d common nails at 4” on center at edge and 12” on center in the field</td>
</tr>
<tr>
<td>K&amp;C 24</td>
<td>Gypsum wallboard on Side 1, Side 2 unsheathed</td>
<td>Screws</td>
</tr>
<tr>
<td>K&amp;C 25</td>
<td>Gypsum wallboard on Side 1, Side 2 unsheathed</td>
<td>Roofing Nails</td>
</tr>
<tr>
<td>K&amp;C 26</td>
<td>Oriented strand board on Side 1, gypsum wallboard on Side 2</td>
<td>Screws</td>
</tr>
<tr>
<td>K&amp;C 27</td>
<td>Oriented strand board on Side 1, gypsum wallboard on Side 2</td>
<td>Roofing Nails</td>
</tr>
<tr>
<td>Oliva 1, 2</td>
<td>1/2 inch gypsum on Side 1, Side 2 unsheathed Monotonic loading.</td>
<td>Drywall nails, 1-1/4 in. long at 8” on center.</td>
</tr>
<tr>
<td>Oliva 3, 4</td>
<td>1/2 inch gypsum on Side 1, Side 2 unsheathed Static cyclic loading.</td>
<td>Drywall nails, 1-1/4 in. long at 8” on center.</td>
</tr>
<tr>
<td>Oliva 5, 6, 5’, 6’</td>
<td>1/2 inch gypsum on Side 1, Side 2 unsheathed. Dynamic cyclic loading.</td>
<td>Drywall nails, 1-1/4 in. long at 8” on center.</td>
</tr>
<tr>
<td>Z&amp;G GBN1, 2</td>
<td>Gypsum wallboard on Side 1, Side 2 unsheathed. Dynamic cyclic loading.</td>
<td>5d sheetrock nails at 7” on center.</td>
</tr>
<tr>
<td>Z&amp;G GBN3, 4</td>
<td>Gypsum wallboard on Side 1, Side 2 unsheathed. Dynamic cyclic loading.</td>
<td>6d sheetrock nails at 7” on center.</td>
</tr>
</tbody>
</table>
### Table 2:
**Results of Gypsum Drywall Tests**

<table>
<thead>
<tr>
<th>TEST</th>
<th>PANEL THICK.</th>
<th>CURVE</th>
<th>MAX. SHEAR LOAD</th>
<th>INITIAL STIFF.</th>
<th>SECANT STIFF.</th>
<th>ENERGY DISS.</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Units</td>
<td></td>
<td></td>
<td>STIFF.</td>
<td>STIFF.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>lb/foot</td>
<td>lb/inch/foot</td>
<td>lb/inch/foot</td>
<td>Inch-lb/foot</td>
</tr>
<tr>
<td>APA-26</td>
<td>0.50</td>
<td>Monotonic</td>
<td>400</td>
<td>600</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>K&amp;C-24</td>
<td>0.50</td>
<td>Monotonic</td>
<td>280</td>
<td>6000</td>
<td>720</td>
<td>50</td>
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<tr>
<td>K&amp;C-24</td>
<td>0.50</td>
<td>Stabilized</td>
<td>230</td>
<td>3800</td>
<td>920</td>
<td>20</td>
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<tr>
<td>K&amp;C-25</td>
<td>0.50</td>
<td>Monotonic</td>
<td>390</td>
<td>4800</td>
<td>500</td>
<td>70</td>
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<tr>
<td>K&amp;C-25</td>
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<td>Stabilized</td>
<td>230</td>
<td>6000</td>
<td>590</td>
<td>20</td>
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<tr>
<td>M-GB1-B</td>
<td>0.50</td>
<td>Maximum</td>
<td>640</td>
<td>3500</td>
<td>1100</td>
<td>N/A</td>
</tr>
<tr>
<td>M-GB2</td>
<td>0.50</td>
<td>Maximum</td>
<td>640</td>
<td>2900</td>
<td>2300</td>
<td>N/A</td>
</tr>
<tr>
<td>Oliva-2</td>
<td>0.50</td>
<td>Monotonic</td>
<td>250</td>
<td>960</td>
<td>230</td>
<td>N/A</td>
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<tr>
<td>Oliva-3</td>
<td>0.50</td>
<td>Cyclic Static</td>
<td>170</td>
<td>930</td>
<td>310</td>
<td>*</td>
</tr>
<tr>
<td>Z&amp;G GBN3</td>
<td>*</td>
<td>Cyclic Dynamic</td>
<td>535</td>
<td>*</td>
<td>787</td>
<td>*</td>
</tr>
<tr>
<td>Z&amp;G GBN3</td>
<td>*</td>
<td>Cyclic Dynamic</td>
<td>590</td>
<td>*</td>
<td>590</td>
<td>*</td>
</tr>
<tr>
<td>Freeman-3</td>
<td>1.00</td>
<td>Dynamic</td>
<td>640</td>
<td>1200</td>
<td>570</td>
<td>*</td>
</tr>
<tr>
<td>Freeman-5</td>
<td>1.00</td>
<td>Dynamic</td>
<td>*</td>
<td>1800</td>
<td>*</td>
<td>*</td>
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<tr>
<td>Rihal-P4</td>
<td>0.625</td>
<td>Cyclic Static</td>
<td>150</td>
<td>1300</td>
<td>380</td>
<td>50</td>
</tr>
</tbody>
</table>

**NOTES:**
1. *Initial stiffness is determined as the tangent at initial loading.*
2. *Secant stiffness is determined at maximum load.*
3. *Energy is determined using a backbone curve for cyclic test.*
### Table 3: Damage Data from Oliva

<table>
<thead>
<tr>
<th>TYPE OF TEST</th>
<th>TOP DISPLACEMENT ( % DRIFT RATIO )</th>
<th>LOAD CARRIED</th>
<th>DAMAGE LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monotonic (Wall 2)</td>
<td>0.3”-0.4” (0.3 – 0.4)</td>
<td>140-170 lb/ft</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>0.5”-0.6” (0.5 – 0.6)</td>
<td>190-200 lb/ft</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>0.6”-1” (0.6 to 1.0)</td>
<td>Maximum 245 lb/ft</td>
<td>Sheathing corners pull away from frame</td>
</tr>
<tr>
<td>Cyclic Static (Wall 4)</td>
<td>0.1”-0.2” (0.1 – 0.2)</td>
<td>90-100 lb/ft</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>0.5” (0.5)</td>
<td>160 lb/ft</td>
<td>All Nails Popped</td>
</tr>
<tr>
<td></td>
<td>0.75” and more (&gt; 0.8)</td>
<td>Maximum 170 lb/ft</td>
<td>B</td>
</tr>
<tr>
<td>Test 1</td>
<td>Test 2</td>
<td>Test 3</td>
<td>Test 4</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Fastener</td>
<td>Nails</td>
<td>Screws</td>
<td>Screws</td>
</tr>
<tr>
<td>Fastener spacing, inch</td>
<td>8</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Loading protocol</td>
<td>Monotonic</td>
<td>Monotonic</td>
<td>Monotonic</td>
</tr>
<tr>
<td>Constraint at top of wall</td>
<td>Fixed</td>
<td>Free</td>
<td>Fixed</td>
</tr>
<tr>
<td>Wall Openings</td>
<td>Door</td>
<td>Door</td>
<td>Door</td>
</tr>
<tr>
<td>Method of construction</td>
<td>Floating Edge</td>
<td>Floating Edge</td>
<td>Floating Edge</td>
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<tr>
<td>Innovative construction method</td>
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<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Repair and retest</td>
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<td>None</td>
<td>None</td>
</tr>
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<table>
<thead>
<tr>
<th>Test 7</th>
<th>Test 8</th>
<th>Test 9</th>
<th>Test 10</th>
<th>Test 11</th>
<th>Test 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fastener</td>
<td>Screws</td>
<td>Nails</td>
<td>Screws</td>
<td>Screws</td>
<td>Screws</td>
</tr>
<tr>
<td>Fastener spacing, inch</td>
<td>16</td>
<td>8</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Loading protocol</td>
<td>Cyclic</td>
<td>Monotonic</td>
<td>Monotonic</td>
<td>Monotonic</td>
<td>Cyclic</td>
</tr>
<tr>
<td>Constraint at top of wall</td>
<td>Free</td>
<td>Fixed</td>
<td>Fixed</td>
<td>Fixed</td>
<td>Fixed</td>
</tr>
<tr>
<td>Wall Openings</td>
<td>Door</td>
<td>Door</td>
<td>Door</td>
<td>Door and Window</td>
<td>Door and Window</td>
</tr>
<tr>
<td>Method of construction</td>
<td>Floating Edge</td>
<td>Top Sill Fastened</td>
<td>Top Sill Fastened</td>
<td>Floating Edge</td>
<td>Floating Edge</td>
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<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Repair and retest</td>
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<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>TEST 13</td>
<td>TEST 14</td>
<td>TEST 15</td>
<td>TEST 16</td>
<td>TEST 17</td>
</tr>
<tr>
<td>------------------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Fastener</td>
<td>Screws</td>
<td>Screws</td>
<td>Screws</td>
<td>Nails</td>
<td>Screws</td>
</tr>
<tr>
<td>spacing, inch</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>8</td>
<td>16</td>
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<tr>
<td>Loading protocol</td>
<td>Cyclic</td>
<td>Cyclic</td>
<td>Cyclic</td>
<td>Cyclic</td>
<td>Cyclic</td>
</tr>
<tr>
<td>Constraint at top of wall</td>
<td>Fixed</td>
<td>Fixed</td>
<td>Free</td>
<td>Fixed</td>
<td>Fixed</td>
</tr>
<tr>
<td>Wall Openings</td>
<td>Door and Window</td>
<td>Door</td>
<td>Door</td>
<td>Door</td>
<td>Door with Door Jamb and Trim</td>
</tr>
<tr>
<td>Method of construction</td>
<td>Floating Edge</td>
<td>Floating Edge</td>
<td>Floating Edge</td>
<td>Floating Edge</td>
<td>Floating Edge</td>
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<td>Innovative construction method</td>
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<td>None</td>
<td>None</td>
<td>None</td>
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<tr>
<td>Repair and retest</td>
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<td>50% Damage Level</td>
<td>50% Damage Level</td>
<td>50% Damage Level</td>
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### Table 5: Fastener Parameters

<table>
<thead>
<tr>
<th>FASTENER</th>
<th>GEOMETRY</th>
<th>SPACINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screw</td>
<td>#6 x 1.25 inch long Black Coarse Drywall Screws – Bugle head design</td>
<td>16 inches on center</td>
</tr>
<tr>
<td></td>
<td><img src="image1" alt="Screw Diagram" /></td>
<td>8 inches on center</td>
</tr>
<tr>
<td>Black-Finish Pan Washer Head Screw</td>
<td>#8 x 1.25 inch long – Used as part of the Innovative System A</td>
<td>16 inches on center</td>
</tr>
<tr>
<td>Oval Head Phillips with Countersunk Washer</td>
<td>#8 x 1.25 inch long – Used as part of the Innovative System A</td>
<td>16 inches on center</td>
</tr>
<tr>
<td>Drywall Nail</td>
<td>No. 13 gage, 1-5/8” long, 19/64” head</td>
<td>8 inches on center</td>
</tr>
</tbody>
</table>
### Table 6:
**Displacement Control for Cyclic Test Protocol**

<table>
<thead>
<tr>
<th>CYCLE</th>
<th>CYCLE TYPE</th>
<th>MAGNITUDE</th>
<th>DRIFT (%)</th>
<th>DEFLECTION AT TOP OF WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,3,4,5,6</td>
<td>Initiation</td>
<td>0.050Δ</td>
<td>0.057</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>Primary</td>
<td>0.075Δ</td>
<td>0.085</td>
<td>0.08</td>
</tr>
<tr>
<td>8,9,10,11,12,13</td>
<td>Trailing</td>
<td>0.056Δ</td>
<td>0.063</td>
<td>0.06</td>
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<tr>
<td>14</td>
<td>Primary</td>
<td>0.10Δ</td>
<td>0.113</td>
<td>0.11</td>
</tr>
<tr>
<td>15,16,17,18,19,20</td>
<td>Trailing</td>
<td>0.075Δ</td>
<td>0.085</td>
<td>0.08</td>
</tr>
<tr>
<td>21</td>
<td>Primary</td>
<td>0.20Δ</td>
<td>0.226</td>
<td>0.21</td>
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<td>22,23,24</td>
<td>Trailing</td>
<td>0.15Δ</td>
<td>0.170</td>
<td>0.16</td>
</tr>
<tr>
<td>25</td>
<td>Primary</td>
<td>0.30Δ</td>
<td>0.339</td>
<td>0.32</td>
</tr>
<tr>
<td>26,27,28</td>
<td>Trailing</td>
<td>0.225Δ</td>
<td>0.254</td>
<td>0.24</td>
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<tr>
<td>29</td>
<td>Primary</td>
<td>0.40Δ</td>
<td>0.452</td>
<td>0.42</td>
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<td>30,31</td>
<td>Trailing</td>
<td>0.300Δ</td>
<td>0.339</td>
<td>0.32</td>
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<tr>
<td>32</td>
<td>Primary</td>
<td>0.700Δ</td>
<td>0.791</td>
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<td>33,34</td>
<td>Trailing</td>
<td>0.525Δ</td>
<td>0.593</td>
<td>0.55</td>
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<tr>
<td>35</td>
<td>Primary</td>
<td>1.000Δ</td>
<td>1.113</td>
<td>1.05</td>
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<td>36,37</td>
<td>Trailing</td>
<td>0.750Δ</td>
<td>0.848</td>
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<td>38</td>
<td>Primary</td>
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<td>1.670</td>
<td>1.58</td>
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<tr>
<td>39,40</td>
<td>Trailing</td>
<td>1.125Δ</td>
<td>1.127</td>
<td>1.18</td>
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<tr>
<td>41</td>
<td>Primary</td>
<td>2.000Δ</td>
<td>2.260</td>
<td>2.10</td>
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<tr>
<td>42,43</td>
<td>Trailing</td>
<td>1.500Δ</td>
<td>1.695</td>
<td>1.58</td>
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<td>44</td>
<td>Primary</td>
<td>2.500Δ</td>
<td>2.825</td>
<td>2.63</td>
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<td>45,46</td>
<td>Trailing</td>
<td>1.875Δ</td>
<td>2.119</td>
<td>1.97</td>
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<tr>
<td>47</td>
<td>Primary</td>
<td>3.000Δ</td>
<td>3.390</td>
<td>3.15</td>
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<tr>
<td>48,49</td>
<td>Trailing</td>
<td>2.250Δ</td>
<td>2.543</td>
<td>2.36</td>
</tr>
<tr>
<td>50</td>
<td>Primary</td>
<td>3.500Δ</td>
<td>3.955</td>
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</tr>
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<td>51,52</td>
<td>Trailing</td>
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<td>2.966</td>
<td>2.76</td>
</tr>
<tr>
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<td>Primary</td>
<td>4.000Δ</td>
<td>4.520</td>
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<td>3.390</td>
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<td>Primary</td>
<td>4.000Δ</td>
<td>4.520</td>
<td>4.20</td>
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### Table 7: Instrumentation for Testing

<table>
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<tr>
<th>CHANNEL</th>
<th>MEASURAND</th>
<th>INSTRUMENT</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>Time</td>
<td>Data Logger internal clock</td>
</tr>
<tr>
<td>1</td>
<td>Lateral displacement at the base of the wall.</td>
<td>1-inch LVDT</td>
</tr>
<tr>
<td>2</td>
<td>Vertical displacement at the base of the door jamb, furthest from the loaded end.</td>
<td>1-inch LVDT</td>
</tr>
<tr>
<td>3</td>
<td>Vertical displacement at the base of the door jamb, closest to the loaded end.</td>
<td>1-inch LVDT</td>
</tr>
<tr>
<td>4</td>
<td>Out-of-plane displacement of the panels 3’-0” above the bottom sill in the doorway.</td>
<td>2-inch LVDT</td>
</tr>
<tr>
<td>5</td>
<td>Lateral displacement of the actuator.</td>
<td>15-inch wire transducer</td>
</tr>
<tr>
<td>6</td>
<td>Lateral force applied by the actuator.</td>
<td>20-kip load cell</td>
</tr>
<tr>
<td>7</td>
<td>Lateral displacement at the top of the wall.</td>
<td>15-inch wire transducer</td>
</tr>
<tr>
<td>9</td>
<td>Strain displacement of narrow pier – quadrants 2 and 4</td>
<td>15-inch wire transducer</td>
</tr>
<tr>
<td>10</td>
<td>Strain displacement of narrow pier – quadrants 1 and 3</td>
<td>15-inch wire transducer</td>
</tr>
<tr>
<td>11</td>
<td>Strain displacement of wide pier – quadrants 2 and 4</td>
<td>15-inch wire transducer</td>
</tr>
<tr>
<td>12</td>
<td>Strain displacement of wide pier – quadrants 1 and 3</td>
<td>15-inch wire transducer</td>
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### Table 8: Summary of Test Data

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<tr>
<th>TEST NO.</th>
<th>DATE TESTED</th>
<th>MAX. LOAD RESISTED</th>
<th>LENGTH OF WALL W/O OPENINGS</th>
<th>MAX. LOAD PER UNIT LENGTH</th>
<th>MAX. DRIFT</th>
<th>DRIFT AT MAX. LOAD</th>
<th>ENERGY</th>
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<tr>
<td></td>
<td></td>
<td>lbs.</td>
<td>feet</td>
<td>plf</td>
<td>inch-lb</td>
<td></td>
<td></td>
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<td>1</td>
<td>April 13</td>
<td>6195</td>
<td>13.20</td>
<td>469</td>
<td>3.85</td>
<td>0.68</td>
<td>9777</td>
</tr>
<tr>
<td>2</td>
<td>May 17</td>
<td>5289</td>
<td>13.25</td>
<td>399</td>
<td>3.91</td>
<td>1.87</td>
<td>9751</td>
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<td>3</td>
<td>June 2</td>
<td>8789</td>
<td>13.23</td>
<td>664</td>
<td>0.91</td>
<td>0.84</td>
<td>5762</td>
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<tr>
<td>4</td>
<td>June 14</td>
<td>11461</td>
<td>13.18</td>
<td>869</td>
<td>3.84</td>
<td>1.20</td>
<td>16938</td>
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<tr>
<td>5</td>
<td>June 23</td>
<td>8357</td>
<td>13.19</td>
<td>634</td>
<td>3.97</td>
<td>1.20</td>
<td>10757</td>
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<td>6</td>
<td>July 5</td>
<td>8031</td>
<td>13.15</td>
<td>611</td>
<td>4.48</td>
<td>1.80</td>
<td>49639</td>
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<td>August 10</td>
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<td>13.19</td>
<td>378</td>
<td>3.24</td>
<td>0.96</td>
<td>47586</td>
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<td>Nov. 2</td>
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<td>640</td>
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<td>0.72</td>
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<td>Nov. 16</td>
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<td>520</td>
<td>4.06</td>
<td>0.72</td>
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<td>560</td>
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<td>Sept. 8</td>
<td>5157</td>
<td>10.20</td>
<td>506</td>
<td>4.52</td>
<td>0.67</td>
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<td>10.20</td>
<td>612</td>
<td>4.71</td>
<td>0.80</td>
<td>65689</td>
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<td>13</td>
<td>Oct. 20</td>
<td>7696</td>
<td>10.15</td>
<td>758</td>
<td>5.60</td>
<td>2.16</td>
<td>105322</td>
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<tr>
<td>14</td>
<td>Dec. 1</td>
<td>7948</td>
<td>13.19</td>
<td>603</td>
<td>1.16</td>
<td>0.74</td>
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<td>14R</td>
<td>Dec. 8</td>
<td>6784</td>
<td>13.19</td>
<td>514</td>
<td>4.30</td>
<td>0.98</td>
<td>50501</td>
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<tr>
<td>15</td>
<td>Dec. 20</td>
<td>4973</td>
<td>13.20</td>
<td>377</td>
<td>1.19</td>
<td>1.17</td>
<td>7032</td>
</tr>
<tr>
<td>15R</td>
<td>Jan. 11</td>
<td>6144</td>
<td>13.20</td>
<td>466</td>
<td>4.95</td>
<td>2.23</td>
<td>66445</td>
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<td>16</td>
<td>Jan. 26</td>
<td>7893</td>
<td>13.18</td>
<td>599</td>
<td>1.16</td>
<td>0.76</td>
<td>18346</td>
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<td>16R</td>
<td>Feb. 2</td>
<td>6341</td>
<td>13.18</td>
<td>481</td>
<td>4.87</td>
<td>2.89</td>
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<td>Feb. 15</td>
<td>9948</td>
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<td>753</td>
<td>4.96</td>
<td>0.89</td>
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Table 9:
Damage Thresholds of Percent Drift for Monotonic Tests

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<tr>
<th>DAMAGE STATE</th>
<th>TEST 1 FRONT</th>
<th>TEST 1 BACK</th>
<th>TEST 2 FRONT</th>
<th>TEST 2 BACK</th>
<th>TEST 3 FRONT</th>
<th>TEST 3 BACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking of Paint over Fastener Head</td>
<td>0.254</td>
<td>0.254</td>
<td>0.503</td>
<td>0.374</td>
<td>0.939</td>
<td>1.008</td>
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<tr>
<td>Cracking of Wallboard at Wall Penetration</td>
<td>0.240</td>
<td>0.760</td>
<td>0.200</td>
<td>0.200</td>
<td>0.227</td>
<td>0.262</td>
</tr>
<tr>
<td>Crushing of Wallboard at Perimeter</td>
<td>1.758</td>
<td>0.254</td>
<td>1.050</td>
<td>1.050</td>
<td>0.778</td>
<td>0.778</td>
</tr>
<tr>
<td>Cracking of Joint at Out-of-Plane Wall</td>
<td>0.760</td>
<td>0.760</td>
<td>0.503</td>
<td>0.503</td>
<td>0.778</td>
<td>N/A</td>
</tr>
<tr>
<td>Cracking of Vertical Butt Joint</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cracking of Horizontal Wall Joint</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Local Buckling of Panel at Wall Penetration</td>
<td>0.525</td>
<td>0.254</td>
<td>0.241</td>
<td>0.241</td>
<td>0.262</td>
<td>0.262</td>
</tr>
<tr>
<td>Global Buckling of Panel</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<table>
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<th>TEST 4 FRONT</th>
<th>TEST 4 BACK</th>
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<th>TEST 5 BACK</th>
<th>TEST 8 FRONT</th>
<th>TEST 8 BACK</th>
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<tbody>
<tr>
<td>Cracking of Paint over Fastener Head</td>
<td>0.735</td>
<td>0.735</td>
<td>0.498</td>
<td>0.498</td>
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<td>Cracking of Wallboard at Wall Penetration</td>
<td>0.240</td>
<td>0.240</td>
<td>0.220</td>
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<td>0.263</td>
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<td>Crushing of Wallboard at Perimeter</td>
<td>0.498</td>
<td>0.751</td>
<td>0.498</td>
<td>0.751</td>
<td>1.264</td>
<td>NR</td>
</tr>
<tr>
<td>Cracking of Joint at Out-of-Plane Wall</td>
<td>1.521</td>
<td>0.994</td>
<td>0.498</td>
<td>N/A</td>
<td>1.264</td>
<td>NR</td>
</tr>
<tr>
<td>Cracking of Vertical Butt Joint</td>
<td>N/A</td>
<td>0.761</td>
<td>N/A</td>
<td>N/A</td>
<td>0.509</td>
<td>0.790</td>
</tr>
<tr>
<td>Cracking of Horizontal Wall Joint</td>
<td>N/A</td>
<td>4.063</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>2.678</td>
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<tr>
<td>Local Buckling of Panel at Wall Opening</td>
<td>0.527</td>
<td>0.527</td>
<td>1.001</td>
<td>1.001</td>
<td>0.378</td>
<td>0.263</td>
</tr>
<tr>
<td>Global Buckling of Panel</td>
<td>2.039</td>
<td>1.437</td>
<td>2.039</td>
<td>1.437</td>
<td>1.500</td>
<td>1.493</td>
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<tr>
<td>Misc. - Cracking of Panel not at Opening</td>
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<td></td>
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<td></td>
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<td>0.790</td>
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<table>
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<th>DAMAGE STATE</th>
<th>TEST 9 FRONT</th>
<th>TEST 9 BACK</th>
<th>TEST 10 FRONT</th>
<th>TEST 10 BACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking of Paint over Fastener Head</td>
<td>0.971</td>
<td>1.244</td>
<td>1.018</td>
<td>1.247</td>
</tr>
<tr>
<td>Cracking of Wallboard at Wall Penetration</td>
<td>0.213</td>
<td>0.213</td>
<td>0.267</td>
<td>0.508</td>
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<tr>
<td>Crushing of Wallboard at Perimeter</td>
<td>0.750</td>
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<td>2.991</td>
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<td>Cracking of Joint at Out-of-Plane Wall</td>
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<td>0.484</td>
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<tr>
<td>Cracking of Vertical Butt Joint</td>
<td>1.003</td>
<td>0.750</td>
<td>0.746</td>
<td>1.018</td>
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<td>Cracking of Horizontal Wall Joint</td>
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<td>Global Buckling of Panel</td>
<td>2.201</td>
<td>4.049</td>
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### Table 10: 
Damage Thresholds of Drift for Cyclic Tests

<table>
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<th>DAMAGE STATE</th>
<th>TEST 6 FRONT</th>
<th>TEST 6 BACK</th>
<th>TEST 7 FRONT</th>
<th>TEST 7 BACK</th>
<th>TEST 11 FRONT</th>
<th>TEST 11 BACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking of Paint over Fastener Head</td>
<td>0.34</td>
<td>0.18</td>
<td>0.250</td>
<td>0.250</td>
<td>0.524</td>
<td>0.472</td>
</tr>
<tr>
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<td>0.34</td>
<td>0.24</td>
<td>0.250</td>
<td>0.250</td>
<td>0.524</td>
<td>0.472</td>
</tr>
<tr>
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<td>0.24</td>
<td>0.24</td>
<td>0.090</td>
<td>0.090</td>
<td>0.121</td>
<td>0.258</td>
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<td>Cracking of Wallboard at Wall Penetration</td>
<td>0.24</td>
<td>0.24</td>
<td>0.120</td>
<td>0.120</td>
<td>0.121</td>
<td>0.258</td>
</tr>
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<td>(+21)</td>
<td>(+17)</td>
<td>(+17)</td>
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<td>(+21)</td>
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<td>Crushing of Wallboard at Perimeter</td>
<td>2.00</td>
<td>1.25</td>
<td>0.777</td>
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<td>0.777</td>
<td>NR</td>
<td>2.376</td>
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<td>(+38)</td>
<td>(+32)</td>
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<td>Cracking of Vertical Butt Joint</td>
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<td>0.301</td>
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<td>(+27)</td>
<td>(+31)</td>
<td>(+28)</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>N/A</td>
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<td>Cracking of Vertical Out-of-Plane Joint</td>
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<td>0.25</td>
<td>0.301</td>
<td>0.359</td>
<td>0.785</td>
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<td>0.36</td>
<td>0.25</td>
<td>0.419</td>
<td>0.359</td>
<td>0.785</td>
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<td>(+32)</td>
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<td>Local Buckling of Panel at Wall Penetration</td>
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<td>NOTE A</td>
<td>0.419</td>
<td>0.359</td>
<td>0.130</td>
<td>0.258</td>
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<td></td>
<td>0.75</td>
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<td>0.419</td>
<td>0.359</td>
<td>0.130</td>
<td>0.258</td>
</tr>
<tr>
<td>Global Buckling of Panel</td>
<td>1.94</td>
<td>4.17</td>
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<td>1.710</td>
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<td>(+50)</td>
<td>(+38)</td>
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**NOTE A –** Local buckling was not seen as a distinct damage state. Instead all re-entrant corners at wall openings showed initial cracking at low levels of drift.
<table>
<thead>
<tr>
<th>DAMAGE STATE</th>
<th>TEST 12</th>
<th>TEST 12</th>
<th>TEST 13</th>
<th>TEST 13</th>
<th>TEST 14</th>
<th>TEST 14</th>
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<tbody>
<tr>
<td></td>
<td>FRONT</td>
<td>BACK</td>
<td>FRONT</td>
<td>BACK</td>
<td>FRONT</td>
<td>BACK</td>
</tr>
<tr>
<td>Cracking of Paint over Fastener Head</td>
<td>0.170</td>
<td>0.277</td>
<td>0.541</td>
<td>0.764</td>
<td>0.475</td>
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</tr>
<tr>
<td>Cracking of Wallboard at Wall Penetration</td>
<td>0.117</td>
<td>0.826</td>
<td>0.085</td>
<td>0.226</td>
<td>0.111</td>
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<td>(+35)</td>
<td>(-20)</td>
<td>(+21)</td>
<td>(+7)</td>
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<td>Crushing of Wallboard at Perimeter</td>
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<td>1.420</td>
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<td>N/A</td>
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<td>N/A</td>
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Table 11: Post-test Stiffness of Frame without Gypsum Wallboard

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<td>lbs./inch/foot</td>
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<td>13060</td>
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<td>0.9717</td>
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Table 12: Contractors for Estimation Work

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<th>LOCATION</th>
<th>ESTIMATED REPLACEMENT COST</th>
<th>YEARS EXPER.</th>
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<td>Tim Wann Construction</td>
<td>Santa Cruz, CA</td>
<td>$655</td>
<td>13</td>
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<td></td>
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<tr>
<td>B</td>
<td>James Jernigan</td>
<td>Jernigan Engineering, Inc.</td>
<td>Danville, CA</td>
<td>$1200</td>
<td>12</td>
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<tr>
<td>C</td>
<td>Andrew Gillespie</td>
<td>A.S. Gillespie &amp; Associates</td>
<td>Pacific Palisades, CA</td>
<td>$896</td>
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### Table 13: Recommended Repair Tasks

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<tr>
<td>Patch and touch-up paint</td>
<td>AC</td>
<td>ABC</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
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<td>Retape and compound</td>
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<td>ABC</td>
<td>ABC</td>
<td>ABC</td>
<td>BC</td>
<td>C</td>
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<td>ABC</td>
<td>ABC</td>
<td>ABC</td>
<td>BC</td>
<td>C</td>
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<td>C</td>
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<td>C</td>
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<td>AC</td>
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<td>ABC</td>
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<td>ABC</td>
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<tr>
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<td>AB</td>
<td>ABC</td>
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<td>BC</td>
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<tr>
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<tr>
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<td>AC</td>
<td>ABC</td>
<td>ABC</td>
<td>BC</td>
<td>C</td>
<td>C</td>
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</tr>
<tr>
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<td>ABC</td>
<td>ABC</td>
<td>ABC</td>
<td>BC</td>
<td>C</td>
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<td>Replace fasteners</td>
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<td>C</td>
<td>AC</td>
<td>ABC</td>
<td>ABC</td>
<td>BC</td>
<td>C</td>
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<tr>
<td>Paint entire wall</td>
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<tr>
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<td>ABC</td>
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<td>N/A</td>
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<td>N/A</td>
<td></td>
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</tr>
</tbody>
</table>
Figure 1:
Lateral Load vs. Displacement (from Oliva)

Figure 2:
Typical Wall Damage Pattern (from Oliva)
Figure 3:
Load vs. Deflection for Glued Gypsum Wallboard (from Oliva)

Figure 4:
Damage Pattern in Glued Gypsum Wallboard Test (from Oliva)
Figure 5:
Test Specimen Type 1 – Door Opening Alone

Figure 6:
Test Specimen Type 2 – Door and Window Opening

All dimensions on Specimen Type 2 are identical to Type 1 except as noted.
Figure 7:
Panel Layout on Front and Back Wall

Window opening shown as dashed

Both Drawings
Doorway is Located
Closest to Actuator

a) Layout of Front Wall – Vertical Butt Joints not Aligned
Openings cut into wallboard before attachment to framing

b) Layout of Back Wall – Vertical Butt Joints Aligned
Openings cut into wallboard after attachment to framing
Figure 8: Details at Edge of Wall

- **TOP OF WALL**
  - C6×16 A36 loading member
  - 2×6 support
  - 2×10 support
  - Double top plate

- **BASE OF WALL**
  - Gap at base 1/4" by design
  - Varies in construction from 0.6" to 0.8"
  - Bottom sill
  - 2×6 support
  - 4×6 support

- **END OF WALL**
  - C6×16 A36 support
  - 3/4" bolt 12" o.c.
  - 2×6 support
  - 4×4 endpoint
  - Wallboard
Figure 9:
Construction of Framing for Wall Specimens

Figure 10:
Connection from Actuator to Drag Member
Figure 11:
Support at Base of Framing

Figure 12:
Specimen #1 after Taping and Compounding
Figure 13: Cyclic Loading Protocol

Figure 14: Fiberglas Tape Reinforcement for Test #12
Figure 15:
Door Frame, Trim and Baseboard for Test #17
For additional information about the instrumentation used see Table 5.

Channel 1  Displacement at base of wall.
Channel 2  Vertical movement at edge of door – long pier
Channel 3  Vertical movement at edge of door – short pier
Channel 4  Out-of-plane movement of gypsum wallboard
Channel 5  Displacement of actuator
Channel 6  Force in actuator
Channel 7  Displacement at top of wall
Channel 9  Strain deformation of short pier
Channel 10  Strain deformation of short pier
Channel 11  Strain deformation of long pier
Channel 12  Strain deformation of long pier

Channel 1 was located 3 inches above the foundation.
Channels 2 and 3 were located 2 inches away from the door opening.
Channels 5 and 6 were located 99.4 inches above the foundation.
Channel 7 was located 93 inches above the foundation.
Channels 9 and 10 were measured over a length of 49 inches and intersected 47.4 inches above the foundation.
Channels 11 and 12 were measured over a length of 110 inches and intersected 47.4 inches above the foundation.
Channels 9, 10, 11 and 12 were oriented at 45° and spaced equally in the middle of the respective pier.
Figure 17:
Crack at Door Penetration – Wall #2 at 1.25% Drift

Figure 18:
Cracking over Fastener Head – Wall #1 at 0.50% Drift
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Cracking at Vertical Joint to Intersecting Wall – Wall #1 at 0.75% Drift

Figure 20:
Local Buckling of Panel at Door Opening – Wall #15r at 0.50% Drift
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Cracking at Window Penetration at Location of Vertical Butt Joint

Figure 22:
Failure of Vertical Butt Joint – Test #16r at 4% Drift
Figure 23:
Failure of Horizontal Joint – Test #17 at 0.75% Drift

Figure 24:
Crushing and Buckling of Wallboard at Door Jamb – Wall #4 at 2% Drift
Figure 25: Buckling of Large Region of Panel – Wall #16r at 4% Drift

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Loss of Entire Panel – Test #17 at 4% Drift
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Load vs. Drift for Test #1 – Nails at 8” o.c.

Figure 29:
Load vs. Drift for Test #2 – Screws at 16” o.c.
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Load vs. Drift for Test #3 – Screws at 16” o.c.

Figure 31:
Load vs. Drift for Test #4 – Screws at 16” o.c.
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Load vs. Drift for Test #5 – Screws at 16” o.c. – Standard Configuration

Figure 33:
Load vs. Drift for Test #8 – Nails at 8” o.c.
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Load vs. Drift for Test #9 – Screws at 16” o.c.

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Load vs. Drift for Test #10 – Screws at 16” o.c.
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Damage of Test #1 at 2% Drift
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Damage of Test #2 at 0.75% Drift

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Damage of Test #2 at 2% Drift
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Damage of Test #4 at 2% Drift
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Damage of Test #5 at 0.75% Drift

Figure 44:
Damage of Test #5 at 2% Drift
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Damage of Test #8 at 0.75% Drift

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Damage of Test #8 at 2% Drift
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Load vs. Drift for Test #7 – Screws at 16” o.c.
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Load vs. Drift for Test #11 – Screws at 16” o.c.

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Load vs. Drift for Test #12 – Screws at 16” o.c. – Innovative System 1
Figure 55:
Load vs. Drift for Test #13 – Screws at 16” o.c. – Innovative System 2
Figure 56:
Load vs. Drift for Test #14 – Screws at 16” o.c. – Damage Test

Figure 57:
Load vs. Drift for Test #14r – Screws at 16” o.c. – Repair Test
Figure 58:
Load vs. Drift for Test #15 – Screws at 16” o.c. – Damage Test

Figure 59:
Load vs. Drift for Test #15r – Screws at 16” o.c. – Repair Test
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Damage of Test #7 at 3% Drift
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Damage of Wall #11 at 2% Drift
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Figure 71:
Damage of Wall #13 at 0.75% Drift

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Damage of Wall #14 Before Repair
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Damage of Wall #14r at 0.75% Drift

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Damage of Wall #14r at 0.75% Drift
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Damage of Wall #15 at 0.75% Drift

Figure 78:
Damage of Wall #15 Before Repair
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Damage of Wall #15r at 0.75% Drift

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Damage of Wall #15r at 2% Drift
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Figure 82:
Damage of Wall #16 Before Repair
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Separation from Framing for Test #11 – Window Opening
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Separation from Framing for Wall #12 – Innovative System 1

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Separation from Framing for Wall #12 – Innovative System 1
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Separation from Framing for Test #13 – Innovative System 2

Figure 100:
Separation from Framing for Test #13 – Innovative System 2
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Separation from Framing for Test #17 – Trim and Baseboard
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Figure 106: Uplift at Door Trimmer for Test #7 – No Middle Anchor Rod
Figure 107:
Framing and Restraint Test for Test #3

\[ y = 13060x - 50.844 \]
\[ R^2 = 0.9717 \]

Figure 108:
Framing and Restraint Test for Test #4

\[ y = 10562x + 78.059 \]
\[ R^2 = 0.966 \]
Figure 109:
Load vs. Drift for Identically Constructed Walls

Figure 110:
Load vs. Drift for Varying Fastener Designs
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Load vs. Drift for Variation in Loading Protocol – Screws at 16” o.c.

Figure 112:
Load vs. Drift for Variation in Loading Protocol – Screws at 16” o.c.
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Fragility Curve for Failure of Horizontal Joint

SOLID BOX = ALL TESTS
CROSS = STANDARD MONOTONIC TESTS
TRIANGLE = STANDARD CYCLIC TESTS
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Damage Cost Ratio Estimates from Estimator A

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Damage Cost Ratio Estimates from Estimator B

![Graph showing the relationship between lateral drift of wall and damage cost ratio.]

Figure 130: Damage Cost Ratio Estimates from Estimator C

![Graph showing the relationship between lateral drift of wall and damage cost ratio.]

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Figure 131:
Fragility Curve of 25%, 50%, 75% and 100% Economic Loss

\[ y = 0.5416 \ln(x) + 1.0719 \quad R^2 = 0.8953 \]
\[ y = 0.7755 \ln(x) + 0.4331 \quad R^2 = 0.9486 \]
\[ y = 1.2338 \ln(x) + 0.032 \quad R^2 = 0.8919 \]

Figure 132:
Models for Prediction of Damage Cost Ratio

\[ y = -0.0211x^2 - 0.0171x + 0.4742 + 0.0265 \quad R^2 = 0.5902 \]
\[ y = 0.3298 \ln(x) + 0.493 \quad R^2 = 0.5692 \]
Figure 133:
Relationship Between Transient Drift and Zero-Load Drift

\[ y = 0.1647x \]

\[ R^2 = 0.9034 \]
Figure 134:
Door Opening Crack at Full Load – Test #17 at 1% Drift

Figure 135:
Door Opening Crack after Unloading – Test #17 at 1% Drift
Figure 136: 
Door Opening Crack at Full Load – Test #17 at 2% Drift

Figure 137: 
Door Opening Crack after Unloading – Test #17 at 2% Drift
APPENDIX A – Survey of Typical Wallframe Construction  
CUREe-Caltech Woodframe Construction Project  
Fall 1999

A research program into the behavior of gypsum drywall and/or stucco construction is being conducted jointly by San Jose State University and Stanford University. It is the goal of the project to study the methods of construction currently used in various regions of California and the United States. Your assistance on completing this survey will allow us to accurately represent the current construction methods. Please answer all questions that you are familiar with, but please do not answer questions that are beyond your area of expertise as this may distort the statistical findings.

If you know other individuals or companies that would be familiar with this subject, please feel free to photocopy and forward this questionnaire to them.

We would appreciate your response before October 31, 1999.

Thank you, your assistance is invaluable.

__________________________  __________________________
Kurt McMullin               Greg Deierlein
Assistant Professor         Associate Professor
San Jose State University   Stanford University

Questionnaire

What state do you work in most often? ____________

Type of work: Circle one answer that represents the most common situation.
   a) Engineering and/or inspection.
   b) General contractor
   c) Retail / supplier
   d) Specialty subcontractor. Please specify ________________
   e) Other. Please specify ________________

Typical framing material.
   Please list the grade, type and size of studs that you commonly use on projects.

Typical thickness of drywall? ______________ inch
Other thicknesses that you often use? ______________ inch
Drywall is usually initially hung from framing using Circle one answer that represents the most common situations.
   a) 1-5/8” phosphate coated nails
   b) 1-5/8” ringshank nails
   c) drywall screws
   d) staples
   e) Other. Please specify ______________

Drywall is usually finished hanging with Circle one answer that represents the most common situations.
   a) 1-5/8” phosphate coated nails
   b) 1-5/8” ringshank nails
   c) drywall screws
   d) staples
   e) Other. Please specify ______________

Typical spacing of the edge fasteners marked above for drywall? __________ inches o.c.
Typical spacing of the field fasteners marked above for drywall? __________ inches o.c.

Material used for taping joints. Circle one answer that represents the most common situations.
   a) paper tape
   b) fiberglass joint tape
   c) Other. Please specify ______________

Typical taping or embedding compound for drywall. Circle one answer that represents the most common situations.
   a) All-purpose compound (wallboard joint compound)
   b) Vinyl ready-mix
   c) Casein
   d) Non-casein compound
   e) Quickset hardening compound (hotmud)
   f) Other. Please specify ______________

Typical topping or finishing compound for drywall. Circle one answer that represents the most common situations.
   a) All-purpose compound.
   b) Vinyl ready-mix
   c) Casein
   d) Non-casein compound
   e) Quickset hardening compound (hotmud)
   f) Other. Please specify ______________
For the shown wall framing, indicate the orientation and size of drywall sheets that would represent common construction. Please indicate whether additional blocking would be placed anywhere and how the panels around the window and doorway would be installed.

Type of construction project that you feel is represented by your answers for this survey. Circle as many as are applicable.

a) Residential track housing.
b) Residential custom construction.
c) Residential multi-family units.
d) Commercial real estate.
e) Other. Please specify _________________

How long have you worked in the industry in the state listed on the first page?

________ years

Have you seen any significant changes in the methods of construction over this period of time? Yes No

If you have, can you explain? ____________________________________________________________

_______________________________________________________________________

Thank you for your assistance. If you would like to receive a free report about the findings of this survey, please include your name and mailing address below.

Name  ________________________________________
Address  ________________________________________

When finished, please mail to:

Kurt McMullin
Department of Civil Engineering
San Jose State University
San Jose, CA 95192-0083
APPENDIX B
Gypsum Wallboard Repair Cost Estimation Sheet
CUREe-Caltech Woodframe Project – Kurt McMullin – 408-924-3855

Test No. 1  Tested on April 13, 2000  Drift Level = 1.25%

Fastener: wallboard nails at 8 inches on center  ½” Standard Wallboard
Configuration: 8 foot by 16 foot wall with a single door penetration

Estimator: __________________________ Phone __________________________
Company: _______________________________ City ___________, State _____

Description of Damage State:
Much the same as damage at ¾% drift but more extensive and covering more of the wall.

Photographs of Damage State:

<table>
<thead>
<tr>
<th>Letter</th>
<th>Description</th>
<th>Photo No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Crack at door penetration.</td>
<td>R2-P15</td>
</tr>
<tr>
<td>B</td>
<td>Damage at nailhead</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Buckling of wall panels</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Vertical crack at end of wall</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Nail head pulled through back of panel at base of wall</td>
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</table>

Repair Work Needed (circle all that apply)
Patch and Touch-up Paint  Complete Repainting
Taping and compounding  Replace fasteners
Replace portions of wallboard panel  Replace entire wallboard panel
Other (please specify) _______________________________________________

Estimated cost of recommended repairs circled above:   $ __________
Estimated cost of replacement of 16-foot long wall:   $ __________

Comments: