13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3431

FRAGILITY CURVES OF WOODFRAME WALLS FOR RESIDENTIAL CONSTRUCTION

Kurt MCMULLIN[1], Dan MERRICK[2], Sajitha KARIM[3], and Rhine DAVIS[3]

SUMMARY

Woodframe residential structures contain a variety of walls: lateral force resisting walls, interior partition walls, and exterior walls. Lateral force resisting walls, commonly called shear walls, provide the engineered resistance to lateral forces from seismic or wind. Interior partition walls are not intended to provide resistance to lateral loads but often provide significant strength and stiffness to the structure. Exterior walls that are not shear walls are required to resist the wind force and transfer it to the diaphragms.

Fragility curves were determined experimentally for interior partition walls and lateral force resisting walls. For interior partition walls, damage thresholds were related to applied drift of the wall. Nineteen interior partition walls were tested and built from double-sided 12 mm gypsum wallboard. Loading was applied in displacement-controlled monotonic, static cyclic, and dynamic cyclic. For lateral force resisting walls, damage thresholds were related to number of cycles of loading. Ten lateral force resisting walls were built from single-sided 9 mm plywood, 9mm and 12 mm oriented-strand board, and 12 mm gypsum wallboard. Loading was applied using an innovative force-control protocol.

Damage thresholds for partition walls included: damage at fastener heads, cracking at wall openings, crushing and/or cracking at perimeter walls, cracking of the panel joints, local buckling of sheathing, and global buckling of sheathing. For lateral force resisting walls, damage thresholds were drifts exceeding 2% and loss of load-resisting capability.

Fragility curves for damage at fastener heads and cracking at wall joints showed 100% of walls damages at low levels of drifts. Other failure modes, such as global bucking and panel joint failure often had only half the walls reach that damage threshold even at drifts as high as 4%. Shear walls were seen to resist their intended design up to 20 cycles of full load application.

[1] Associate Professor, San Jose State University
[2] Lecturer, San Jose State University
[3] Graduate Student Research Assistant, San Jose State University

INTRODUCTION

Damage to residential homes has been recorded in several past earthquakes and levels of economic damage appear to be closely linked with the extent of damage to the wallboard covering of both structural and architectural walls. Milne (1931) 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.

During the 1971 San Fernando earthquake damage to residential construction was substantial and post-earthquake investigations were conducted of 12000 residential structures (Oakeshott, 1975, pp. 329-334). In the 1994 Northridge earthquake, approximately half of the $40 billion dollars in damage were attributed to residential woodframe structures. As a result of this large economic damage, the CUREE-Caltech Woodframe Project was initiated and one task was the experimental evaluation of gypsum wallboard partition walls.

Woodframe structures are built with a wide variety of architectural finishes on the walls; gypsum wallboard is the most common finish used for architectural partitions. Much of the available literature on wall finishes is based upon wall systems where the finish materials are intended to provide lateral restraint of the building.

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. 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) and the significant damage observed in light-frame structures in past earthquakes. This reduced strength requires longer lengths of drywall to resist seismic loads and 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 ½-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 general consensus has been that these buildings need support from shearwalls built from more robust materials, usually plywood or some other wood product.

Engineering of residential construction in California is generally governed by the guidelines of the Uniform Building Code. Non-engineered woodframe construction is identified as conventional construction in the Uniform Building Code (International Council of Building Officials, 1997).

EXPERIMENTAL TEST PROGRAM

The scope of this study was for gypsum wallboard partition walls that might be commonly used in woodframe construction according to the 1997 Uniform Building Code (ICBO, 1997). Fire-resistant walls and horizontal ceilings were beyond the scope of the study.

The primary objectives of the experimental testing for this task were: 1) compare the performance of walls using screws or nails to support the wallboard and evaluate the effect of changing the spacing of fasteners, 2) compare the behavior of the walls for monotonic or cyclic loading protocols, and 3) determine the drift when specific damage thresholds occur.

The interested reader is referred to the final project report for a more complete discussion of the project and testing (McMullin and Merrick, 2002). All test specimens were built similar to Figure 1 and according to the matrix listed in Table 1. The wall dimensions were 8 ft. by 16 ft. (2440 mm by 4880 mm) 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 frames had double top plates, single bottom plates, 4 in. by 4 in. (100 mm by 100 mm) endposts and intermediate single studs at 16 in. (400 mm) on center. All frames were sheathed on both sides with standard ½ inch (13 mm) gypsum sheathing wallboard. 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.

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 than for similar walls without such restraints. To simulate this three-dimensional behavior, the walls were built with orthogonal boundary members along the top, bottom and both ends.

Test Variables

The nail and screw size is the minimum required by the Uniform Building Code (ICBO, 1997), while the 400 mm spacing of screws is the maximum allowed. The 200 mm screw spacing was intended to represent a lower bound on the spacing of screws for residential construction.

Two means of vertical restraint were simulated during testing. 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. A pair of 39 mm diameter anchor rods was installed at each end of the wall to simulate the vertical resistance provided by the intersecting walls. The second means of restraint would be the members supporting the floor above. The top floor of a structure is expected to deflect laterally with little resistance provided by the roofing above 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 resulting in even less 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. To understand the effect of variation in the 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. After wallboard installation and before testing all anchor-rods were tightened to an axial load of 8800 kN via a calibrated torque wrench.

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 when the structure might likely be in a collapse state. The second monotonic loading protocol was developed 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. 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 4000 kN. 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.

Krawinkler et al developed the cyclic loading protocol for the CUREE-Caltech Woodframe Project (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 was denoted as Δ_M. To establish this standard, Test S16MAF was chosen as the specimen closest to the norm of common wall construction. Once Δ_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 first. Figure 2 shows the cyclic protocol displacement control.

Another test variable was the method that the top plate was attached to the wallboard. Floating edge construction refers to installing the top row of fasteners to the vertical studs a certain distance below the top plate and has been recommended by the gypsum wallboard industry for over twenty years to minimize partition separation problems. For this series of experiments, two methods of attachment of the top row of fasteners were used: for floating edge, the top row of fasteners was placed below the sill the maximum distance allowed by the Uniform Building Code (300 mm), and for common practice the fasteners were attached along the top plate at the spacing of the wall framing. All rows below the top were installed the same for all specimens in that they were equally spaced from the bottom of the wallboard panel.

Damage Thresholds. After the 1971 earthquake, building damage was categorized as being severe, moderate or slight (Oakeshott, 1975). Severe damage represented buildings with permanent distortion, separation of the framing from the foundation, portions of the plaster loose or broken free, wallboard requiring 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 that could be achieved by spackling of the plaster or wallboard. Structures were rated moderate when they appeared between these two extremes.

Oliva (1990) defined the observed damage thresholds in the monotonic and cyclic static tests as 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".

For this testing project, a more detailed definition of damage thresholds was developed. A total of eight different forms of damage were defined and monitored during the testing. These were:

1. Cracking of the re-entrant corner at one of the wall openings. This was defined as the initiation of a hairline crack of any length at any one of the corners of the wall openings.

2. Loss of compound or cracking of paint at one fastener head. A permanent, visible damage at any of the fastener heads. This did not include unsightly bulges formed by the fastener as it pulled itself through the backing paper of the wallboard. These bulges could become significant (up to 5 mm), especially at drift levels over two percent. One reason for not including the bulging of fasteners as a damage threshold 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 taped vertical joint to one of the intersecting walls. Initiation of a crack at either of the ends of the wall. This crack forms between the in-plane wall of the specimen and the intersecting wall.

4. Local buckling of the panels. A small compression failure at one of the re-entrant corners of one of the wall openings

5. Cracking of the joint compound or tearing or slipping of the tape at one of the vertical butt-joints. Any visible damage to any of the vertical joints between in-plane panels, whether the joint was located at a wall opening or not.

6. Cracking, tearing or slipping of the joint compound at one of the horizontal wall joints. Any visible damage to any of the horizontal tapered joints between in-plane panels.

7. Crushing of wallboard panels against the intersecting wall, the ceiling, or the foundation along the perimeter of the wall. Local compression failure of a portion of the wallboard due to interference from an orthogonal wall.

8. Buckling of large regions of the wallboard panels.

A damage event was the observation that the threshold had been achieved and the drift was recorded for each damage event. Visual means were used for the observation of each damage event. Damage events were recorded 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. With two faces on eleven specimens, a total of 22 samples were used for the damage thresholds.Type text immediately below subheadings

EXPERIMENTAL TEST RESULTS

Table 1 lists a summary of the force and displacement data collected from the test program. Figure 3 shows the force-displacement data for two identical specimens with different loading protocols. Note that the monotonic test provides a good estimate of the backbone curve of the cyclic test.

Table 2 lists the drift levels when various damage events occurred. Cracking at the door opening usually initiated around a drift of 0.25%, as can be seen in Figure 4. At wall openings, cracks propagate toward the other end of the pier unless a vertical butt joint exists, in which case the crack then follows this joint. The gypsum industry specifically recommends not placing vertical butt joints at the corners of openings to avoid this concern. This crack slowly widens and lengthens with increasing drift, reaching a width of 3 mm at drifts between 0.50 and 0.75% and 6 mm at drifts between 0.60 and 1%. At approximately the same drift (between 0.25 and 0.75%), fastener heads begin to crack the compound and paint topping.

Failure Modes.

While observing the testing, there appeared to be two distinct modes of failure for the sheathing. The actual mode for a specimen 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 pier-rotation 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 compounded joints remained intact, usually throughout 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 joint-failure mode was more similar to a racking behavior, where each panel rotated independently. Cracking of the paint over the fastener heads was usually seen to occur, but complete pull through 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. 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.

Monotonic and Cyclic Wall Behavior.

The behavior of most walls was very similar. The crack at the door opening grows significantly in length until a drift of approximately two percent was reached. Maximum loads are resisted at a drift of approximately 1 to 1.5%. During the pier-rotation failure mode, the wallboard begins to move out-of-plane at the point of maximum load as the fastener heads pull through the back face of the wallboard panel. For the joint-failure mode, damage at the joints becomes prevalent and visible racking of the panels begins to occur after the maximum load is reached. As the drift increases to four percent the wallboard panels remain essentially undeformed but ride out over the top of the fastener heads. 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 the monotonic loading excursion.

Initially it was expected that all damage thresholds would be observed during primary loading cycles for the cyclic loading protocol. This assumption was based upon the belief that most damage would have a dominant factor of drift, but in reality several of the damage thresholds occurred in trailing cycles of loading. Table 2 shows that occasionally low-drift trailing cycles of loading would cause damage events. These events would often occur after primary loading cycles with drift levels similar to the thresholds seen in monotonic tests. This would imply that some form of material degradation and memory exists.

Fastener Damage.

The most common fastener damage was consistently a loss of hold on the wallboard. This resulted from the fastener head pulling though 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 only a few screws and was observed during demolition of the test specimen. This rare occurrence is believed 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.

FRAGILITY CURVES

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. 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 all tests listed in Table 1 and had a maximum sample size of 22 wall faces (two faces for each test specimen). For each damage threshold, the recorded drift level for the event to occur was ranked in increasing order. This data was obtained from the test data summarized in Table 2. 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 5 shows the fragility curve for cracking at the re-entrant corner of the wall opening, cracking of the paint over the fastener head, failure of the vertical joint to the intersecting wall, and crushing at the perimeter of the wall. Almost every test experienced cracking at the wall opening before a drift of approximately 0.5%. The highest drift event was for Test #1, the wall with nails at eight inches on center. It should be noted that damage at the fastener head 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. For this damage threshold, Test #17 recorded the highest drift. Crushing at the perimeter was 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 6 is the fragility curve for local buckling at the wall opening, failure of the vertical butt-joint, global buckling of the wallboard, and failure of the horizontal joint. Failure of the panel joints occurs only with the second mode of failure discussed earlier (racking of the panels). The data for the vertical joints indicates that this threshold was much more likely in the cyclically loaded wall specimens, in fact it only occurred in about 50% of the monotonically loaded specimens. As seen in the 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. 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. 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.

CONCLUSIONS

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

1. Both screws and nails give acceptable performance. 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.

2. 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 the occurrence of an event.

3. 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.

4. 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.

5. 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 wallboard would be required to be removed and replaced.

6. 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.

7. 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.

8. The maximum strength of walls usually occurs at drift ratios between 0.75% and 1.25%.

9. Two exclusive modes of failure were seen in the test specimens. When taped joints have significant strength relative to the strength of the fasteners, the wallboard was seen to pull off the fastener heads and then slide over the intact fasteners (pier-rotation failure mode). In the other mode of failure (joint-failure mode), 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.

10. Global buckling of the wallboard was seen to be closely related to the size of the gap between the panels and the foundation. 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 panel were so free from the fasteners that the panels would slide out, and around the edge of the orthogonal restraint.

11. 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.

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

ACKNOWLEDGEMENTS

The work described in this report was conducted under a contract to Consortium of Universities for Research in Earthquake Engineering (CUREE) as part of the CUREE-Caltech Woodframe Project ("Earthquake Hazard Mitigation of Woodframe Construction"), under a grant administered by the California Office of Emergency Services and funded by the Federal Emergency Management Agency. Additional funding was obtained from the Graduate Research Office of San Jose State University. The authors are grateful for the support received from these two sources. The authors are solely responsible for the information contained in the publication, and that no liability for the information included in the publication is assumed by the Consortium of Universities for Research in Earthquake Engineering, California Institute of Technology, Federal Emergency Management Agency or California Office of Emergency Services.

REFERENCES

1. Adams, Noel, R., 1974. "Monotonic and Cyclic Tests of Timber Shear Walls," Canadian Journal of Civil Engineering, vol. 19, no. 3, pp. 415-422.
2. American Standard of Testing and Manufacturing, 1995, Standard C840.
3. California State Department of Education, 1972. Drywall Taping. California State Department of Education.
4. Federal Emergency Management Agency, 1997. NEHRP Guidelines for the Seismic Rehabilitation of Buildings. Report FEMA-273. October. Washington, DC.
5. International Council of Building Officials, 1997. Uniform Building Code.
6. Karacabeyli, E. and Ceccotti, A., 1996. "Test results on the lateral resistance of nailed shear walls." Proceedings, International Wood Engineering Conference, Baton Rouge, LO.
7. Krawinkler, H.; Parisi, F.; Ibarra, L.; Ayoub, A.; Medina, R., 2001. Development of a Testing Protocol for Woodframe Structures, CUREE Publication No. W-02.
8. Kunnath, S. K.; Mehrain, M.; Gates, W. E., 1994. "Seismic Damage-control Design of Gypsum-roof Diaphragms," Journal of Struct. Engr., vol. 120, January, no. 1, pp. 120-138.
9. McMullin, K. M. and Merrick, D. S., 2002. Seismic Performance of Gypsum Walls – Experimental Test Program. CUREE-Caltech Woodframe Project Report W-12. Richmond, CA.
10. Merrick, Dan S., 1997. Cyclic Comparison Testing of Light Wood Framed Shear Walls. Published electronically at http://www.engr.sjsu.edu/dmerrick/shearwalls/
11. Milne, John, 1939. Earthquakes and Other Earth Movements, 7th Edition. P. Blakiston's Son & Co., Inc. Philadelphia.
12. National Gypsum Company, 2001. Gypsum Wallboard: So Easy to Install, Finish and Repair, You Can Do It Yourself. Published electronically at: http://www.national-gypsum.com/resources/diy/diy.pdf, June 4, 2001
13. Oakeschott, Gordon B., 1975. San Fernando, California Earthquake of 9 February 1971, Bulletin 196, California Division of Mines and Geology, Sacramento, CA.
14. Oliva, Michael G., 1990. "Racking Behavior of Wood-Framed Gypsum Panels under Dynamic Load," Report No. UCB/EERC-85/06, Earthquake Engineering Research Center, University of California, Berkeley.
15. Schmid, Ben L., 1996. "Three-Story Wood Apartment Building," 1994 Northridge Earthquake: Buildings Case Study Project, Proposition 122: Product 3.2, SSC 94-06, Seismic Safety Commission, State of California.
16. Smith, H.A., Vance, V.L., 1996. "Model to Incorporate Architectural Walls in Analyses," Journal of Structural Engineering, vol. 122, no. 4, pp. 431-438.
17. Wolfe, R.W., (1983). "Contribution of Gypsum Wallboard to Racking Resistance of Light Frame Walls." USDA Forest Serv. Res. Pap. FPL 439, Forest Products Lab., Madison, Wisconsin.
18. Zacker, Edwin G. and Gray, Ralph Gareth, 1985. "Dynamic Tests of Wood Framed Shear Walls." Proceedings, Structural Engineers Association of California Annual Convention. San Deigo, CA.

Table 1. Test Matrix and Results

Test Specimen	Total Length of Piers		Maximum Load Resisted		Drift at Maximum Load	Total Energy Dissipated	
	(feet)	(mm)	(lbs/foot)	(N/m)	(percent)	(in.-lb)	(j)
N8MAF	13.20	4025	469	635	0.68	9777	1105
S16MUF	13.25	4040	399	541	1.87	9751	1102
S8MAF	13.18	4020	869	1177	1.20	16938	1914
S16MAF	13.19	4020	634	859	1.20	10757	1215
S16CAF	13.15	4010	611	828	1.80	49639	5608
S16CUF	13.19	4020	378	512	0.96	47586	5376
N8MAC	13.19	4020	640	867	0.72	16635	1879
S16MAC	13.15	4010	520	704	0.72	10547	1191
S16MACW	10.21	3110	560	759	1.42	10715	1211
S16CAFW	10.20	3110	506	685	0.67	62355	7045
S16CAFT	13.21	4025	753	1020	0.89	82864	9362

NOTES

1-) Test Specimen name is in the following format: a b c d e f, where:

a = N for nails or S for screws

b = spacing of fastener in inches

c = M for monotonic loading or C for cyclic loading

d = A when anchor rods were installed in the middle region of the wall, thus forcing the specimen to behave in pure shear or U when these rods were not installed

e = F when floating edge construction was used, thus eliminating all fasteners from the top 12 inches of the framing or C when the wallboard was fastened to the top plate

f = W when the specimen included a window opening, T when door trim and baseboard added, and no value when neither of these.

Table 2. Drift for Various Damage Thresholds

Damage Threshold	Lowest Occurrence		Highest Occurrence[2]		Average Occurrence[3]		Number of Cyclic Tests When Damage Occurred in Primary Loading Cycle[4]
	Mono.[1]	All	Mono.	All	Mono.	All	
Cracking of wallboard at opening	0.20	0.09	0.76	0.76	0.29	0.25	5/8
Cracking of paint over fastener head	0.25	0.18	1.25	1.69	0.67	0.62	7/8
Cracking of the vertical butt-joint	0.51	0.27	7	8	0.80	0.65	3/7
Local buckling of the wallboard	0.24	0.13	1.00	1.00	0.50	0.47	7/7
Cracking of the tapered wall joint	1.00	0.66	11	16	2.58	1.86	2/3
Crushing of the wallboard	0.25	0.25	2.99	1	1.09	1.20	6/6
Global buckling	1.44	1.44	5	8	2.02	2.23	4/5

NOTES

1-) Mono. refers to tests with monotonic loading protocols (sample size = 14), All refers to all tests (sample size = 22)

2-) If the value for the highest occurrence is an integer, then the integer is the number of walls that did not experience the damage threshold

3-) Average occurrence is the average of the walls that did experience a specific damage threshold.

4-) Fraction indicates the number of wall faces with damage event occurring in primary loading cycle divided by the total number of times the damage occurred.

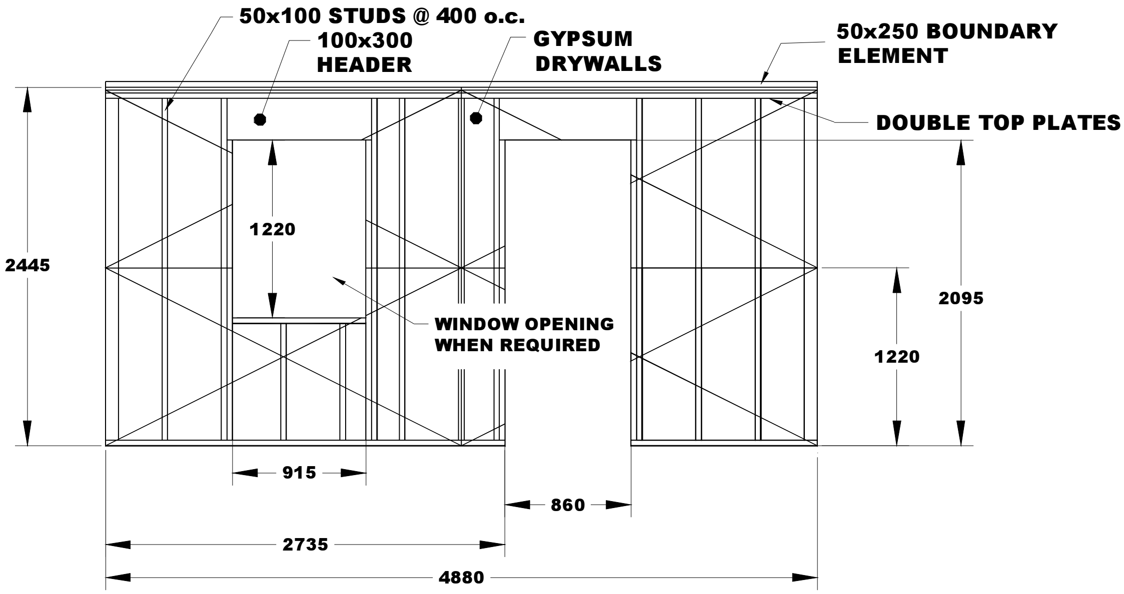

Figure 1. Experimental Test Specimen

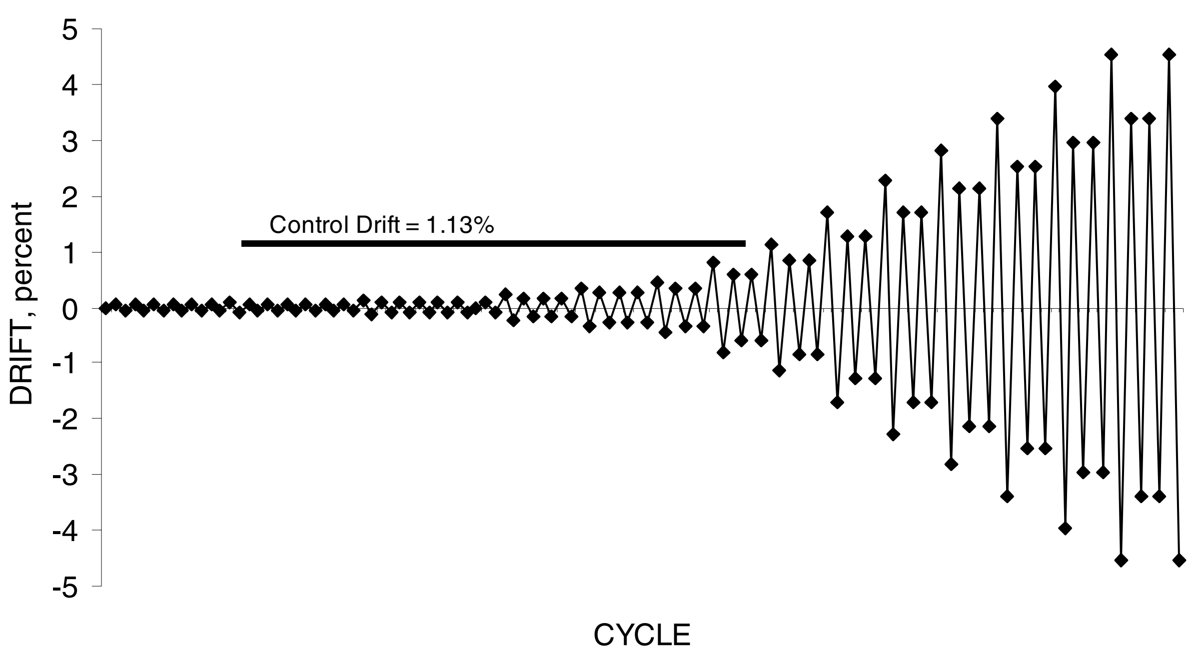

Figure 2. CUREE-Caltech Cyclic Loading Protocol

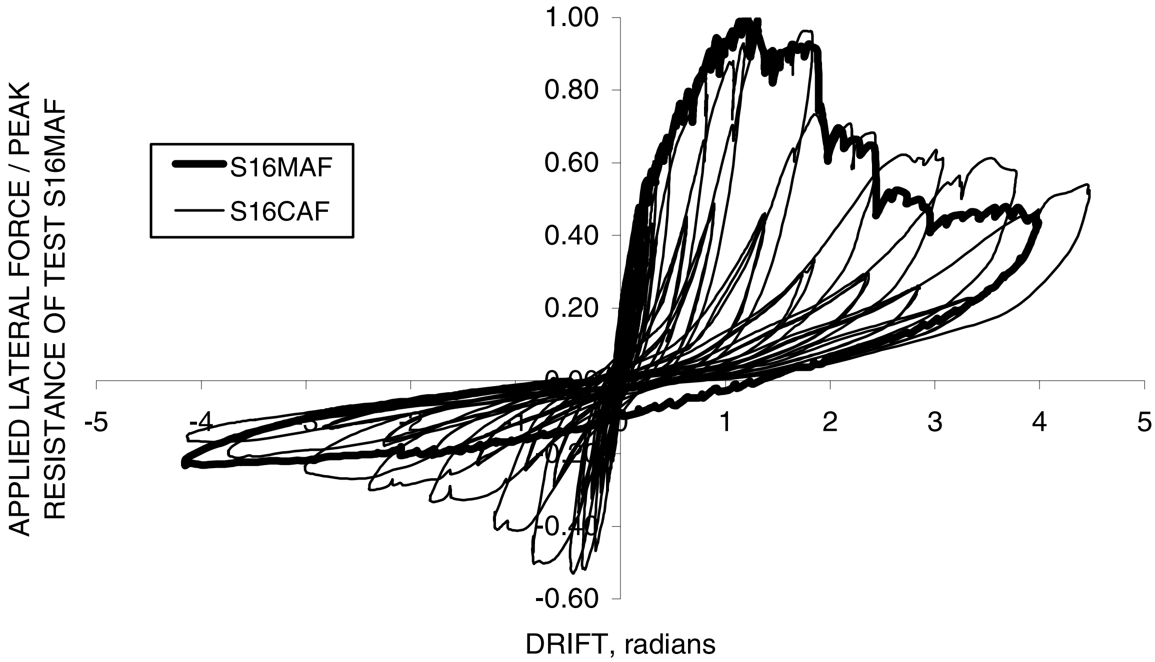

Figure 3. **Comparison of Monotonic vs. Cyclic Load Deformation for Typical Wall Test Specimens**

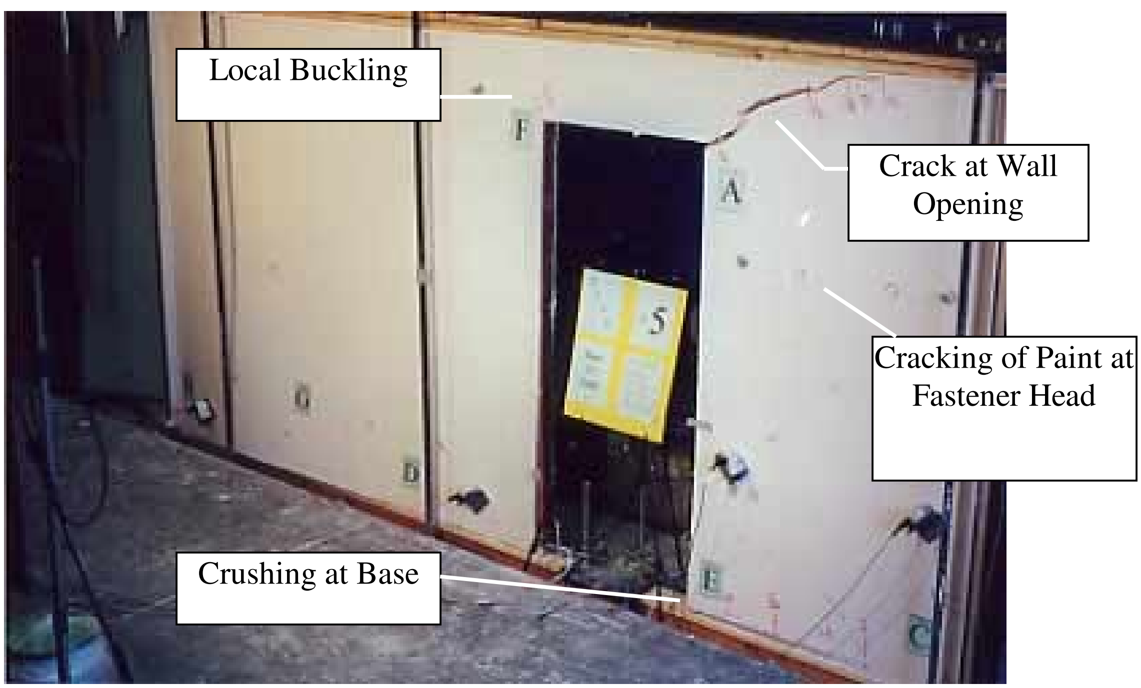

Figure 4. **Photograph of Wall Specimen S16MAF at 2% Drift**

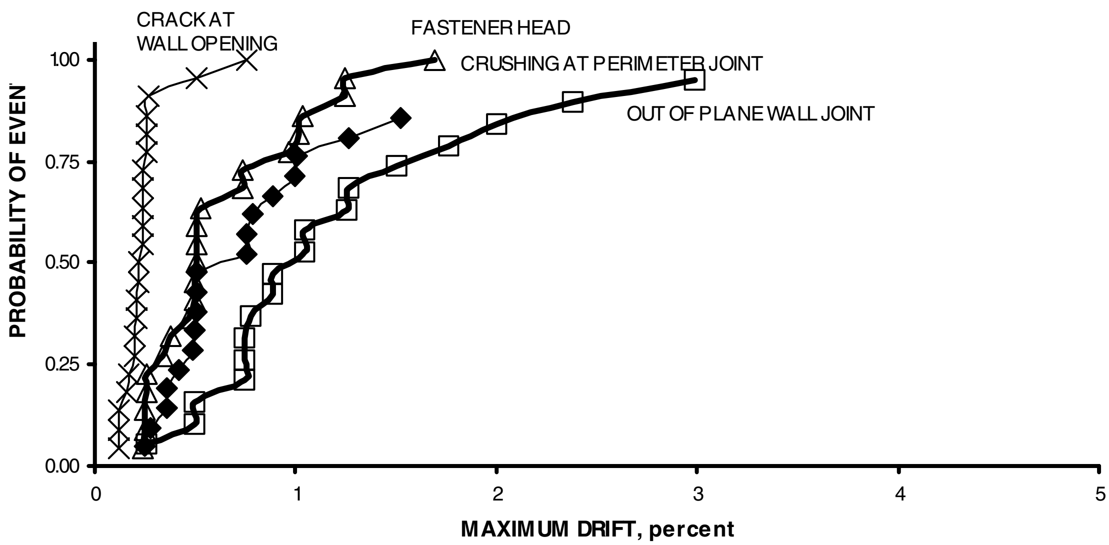

Figure 5. **Fragility Curve for Cracking at Wall Opening, Damage to Fastener Head, Crushing at the Perimeter, and Failure of the Joint to the Out of Plane Walls**

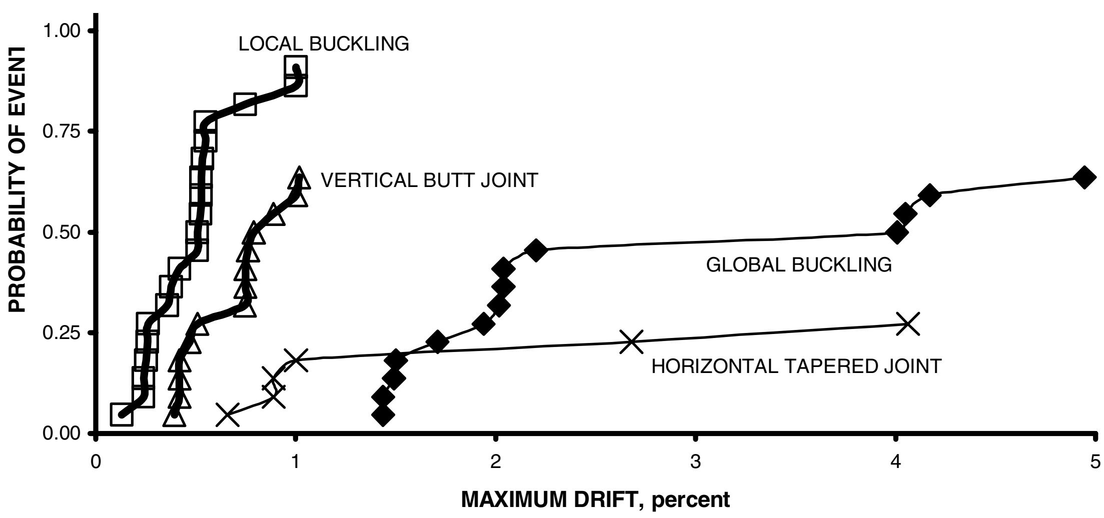

Figure 6. **Fragility Curve for Failure of Vertical Butt Joint, Horizontal Joint, Local Buckling at Door Opening, and Global Buckling of Panel**