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INTERPRETATION OF TEST DATA ON DRYWALL AND STUCCO SHEATHED WOODFRAME SHEAR WALLS

G.C. Hart[1], C.C. Simsir[2], A. Jain[1], and A.P. Dumortier[3]

[1] *Principal, Weidlinger Associates Inc., Marina del Rey, CA 90292, USA*
[2] *Senior Engineer, Weidlinger Associates Inc., Marina del Rey, CA 90292, USA*
[3] *Senior Project Engineer, Weidlinger Associates Inc., Marina del Rey, CA 90292, USA*
Email: hart@wai.com, simsir@wai.com, jain@wai.com, dumortier@wai.com

ABSTRACT :

A wealth of data has become available since 2001 about the performance of drywall and stucco sheathed woodframe walls under cyclic loading. Drywall and stucco are the only lateral force resisting systems in many existing residential buildings in the United States, especially single-family homes built in the 1970s and earlier. Plywood sheathing is minimal or non-existing, and wall finishes provide the shear strength in these light-frame buildings. This paper takes a closer look at the actual laboratory cycle by cycle data from CoLA-UCI (City of Los Angeles – University of California, Irvine) and CUREE-Caltech woodframe test programs, and uses them to clarify the meaning of significant damage as it relates to gypsum sheathed shear walls. This paper can be viewed as an extension of the valuable information in the test program reports by the original authors, with a focus on the interpretation and use of the test data for the evaluation of damage to existing woodframe buildings. Interpretation of the results is useful considering the large stock of these existing buildings that are still susceptible to damage from new events or cumulative damage to their currently partially repaired states. Analysis of the data considers the strength and stiffness loss observed between the initial and later cycles when the wall is loaded to a certain displacement. A loss of strength and stiffness does occur starting at small displacements. Thus, the paper can be valuable to others working on performance based design development. The paper also considers the strength and stiffness recovery of repaired walls.

KEYWORDS: Drywall, stucco, woodframe, existing building, cyclic test

1. INTRODUCTION

Engineers inspecting buildings after an earthquake are frequently posed with the question whether post-earthquake cracks in a drywall shear wall are simply cosmetic or instead indicate significant structural damage to the shear wall. The immediate answer is that the damage on any shear wall is never simply cosmetic because of the lateral earthquake resistance the wall provides to the building. Yet the answer requires clarification on the meaning of the word “significant” in the context of structural damage. This paper aims to clarify this question.

Modern structural analysis visualizes the lateral force resisting system of a wood frame building for seismic and wind loads as being composed of stud framed shear walls sheathed with various types of materials. Structural design criteria for wood buildings built in high seismic areas typically require designated shear walls to be sheathed with plywood on one or both sides of the wall. The other remaining building walls also contribute to the lateral earthquake resistance of the building. These walls are typically sheathed with drywall on both faces (typically interior walls) and with drywall on one face and stucco on the other face of the wall (typically exterior walls). This paper focuses on drywall shear walls that are also called gypsum shear walls. Many of the pre-2000 wood frame buildings in high seismic regions, as well as low seismic regions do not have plywood shear walls and instead utilize a combination of drywall and drywall/stucco shear walls to provide the only lateral load resistance. It is this type of buildings that first provided the motivation for the work described in this paper. We hope that this paper will assist other structural engineers in understanding the performance of wood structures using shear walls for a range of deformation levels.

Life safety protection of occupants for wood buildings has appropriately been the primary focus of structural engineers. This focus has directed attention to the maximum load and displacement capacities of stucco and drywall shear walls or as it is called the Life Safety (or Ultimate) Limit State of structural response. In addition to Life Safety, it is very important to address the other limit states such as the concept of First Major Event (FME) and the Yield Limit State (YLS) discussed in the CoLA-UCI report (2001). The FME has been defined as the first significant limit state that occurs during a test signifying a demarcation between two behavior states. In the case of a shear wall, the FME occurs when the lateral load capacity of the shear wall, upon recycling of the load to the same horizontal wall displacement increment, first drops noticeably from the original load and displacement. The YLS is the point on the force-displacement diagram where the difference in the forces in the first and last cycles, at the same displacement, does not exceed 5%. For the remainder of this paper the YLS will be understood to be the onset of significant structural damage. A study of these limit states will better define the point where significant structural damage first occurs and the method to return this type of damaged building to its pre-earthquake condition. These two topics and others are very important to the civilians we serve as civil engineers after an earthquake and also in the estimation of the financial impact of future earthquakes.

2. TEST PROGRAMS

To plan a good experimental test, either in the confines of a university type laboratory or in the field where full scale buildings are instrumented, one must have as a minimum a preliminary analytical model of the subject of the experiment. Later, when the experiment is performed this model must be evaluated and improved in light of the lessons learned from the experiment. Therefore, all experimental test data is extremely valuable to the structural engineer. This is especially important to acknowledge in this exciting new era of experimental test programs because of the continuous modification and improvement of the test displacement / loading protocol that is part of the experimental programs.

The Structural Engineers Association of Southern California (SEAOSC), The City of Los Angeles (CoLA), Consortium of Universities for Research in Earthquake Engineering (CUREE), Federal Emergency Management Agency (FEMA), and others have recognized this need to better understand the performance of wood frame buildings. With government and other funding, a good base of test data and analysis tools for wood structures were developed by professional structural engineers and university professors. In the mid-1990 and early 2000's a good information base of laboratory test data on the structural components in wood buildings was collected. Tables 1 and 2 provide a summary of the experimental test programs that have drywall experimental test data for cyclic testing protocols.

Table 1 Drywall shear wall experimental testing

Test Program	**Sheathing**		**Nailing**	
	One Side	**Other Side**	**One Side**	**Other Side**
APA 157	1/2"GWB	None	5d cooler @ 7"/7"	None
Dan Merrick	1/2"GWB	None	5d cooler @ 4"/4"	None
http://www.engr.sjsu.edu/dmerrick/shearwalls				
CoLA	1/2" or 5/8"GWB	1/2" or 5/8" GWB	5d cooler @ 7"/7" or 6d cooler @ 4"/4"	5d cooler @ 7"/7" or 6d cooler @ 4"/4"
CUREE W-15	1/2"GWB	1/2" GWB	#6 screw or 5d cooler @8"/8" or 16"/16"	#6 screw or 5d cooler @8"/8" or 16"/16"
CUREE W-25	1/2"GWB	None	#6 screw @ 7"/7"	None

While the focus of this paper is on the analysis of experimental test data it is very important to note that analytical studies also provide valuable insight into the performance of shear walls. An excellent analysis report was written by Deierlein and Kanvinde (2003) titled "Seismic Performance of Gypsum Walls – Analytical Investigation." The aim of the study described in that report was to develop analytical models to predict the seismic performance of gypsum drywall partitions. They also developed fragility models for cracking damage for the prediction of damage and also to aid in post-earthquake investigations. The following quotations are from the 2003 report:

- "The fragility data indicate that cracks around window and door openings reach 1-inch lengths at wall drift ratios between 0.05 to 0.1% and grow to 12-inches at ratios of 0.3 to 0.7% drift."
- "Generally the cracks reach their full lengths and stop growing by wall drift ratios of 1% or roughly 1-inch drift in an 8-foot tall wall."
- "Very early in the loading, cracks initiate at the corners of door and window openings. At larger drifts, local connector failures begin – so called "nail pops" – evident by cracking or spalling of the paint and spackle above the nail or screw heads."
- "Localized damage to the wallboard around the connectors eventually leads to softening of the wall."

These analytical results by Deierlein and Kanvinde (2003) are very important because they indicate that perhaps the study of the cracks in drywalls can provide a good estimate of the inter-story drift of buildings. This would be invaluable in the determination of the loss of strength and stiffness not only in wood buildings but also concrete and steel buildings subjected to earthquake and wind loads.

Table 2 Drywall shear wall experimental testing details

Test Prog.	Institution	Report Date	Number of Specimens	Specimen Size	Opening	Opening Size	Repair	Loading Protocol	Framing
APA 157	APA lab (Rose, Keith)	1996	7 (7x1)	8'x12'	SD or W	SD: 6'x7', W: 6'x6', 6'x5', 6'x4'	No	Monotonic and three unloading cycles	Dry Western Hemlock - Pacific Silver Fir
Dan Merrick website	SJSU (Merrick)	1999	7 (7x1)	8'x13'	None	-	No	Cyclic at constant amplitude	Douglas Fir
CoLA	UCI	2001	108 (36x3)	8'x8'	None	-	No	SPD	Douglas Fir
CUREE W-15	SJSU McMullen	2002	17 (17x1)	8'x16'	PD or PD + W	PD:2'10" x6'10", W: 3'x4'	Yes	CUREE	Hem Fir No.2 or better
CUREE W-25	UCI (Pardoen et al.)	2003	56 (28x2)	8'x16' (one story) and 16'x16' (two stories)	None or PD or GD or PD + W + W	PD: 3'x6'8", GD: 9'9"x7', W: 4'4"x4'	No	CUREE	Douglas Fir No.1 or better

PD: Pedestrian Door GD: Garage Door SD: Sliding Door W: Window

This paper will address the results of tests performed on drywall only as shown in item I of Table 3. We have focused our attention on these test results because all tests were conducted using cyclic displacement controlled testing protocols. Due to the length limitations of this paper we note that an expanded version of our analysis of the University of California, Irvine test results and our analysis of the San Jose State University test results are available in additional papers.

Table 3 Matrix of tests considered

	COLA	**W15 (SJSU)**	**W25 (UCI)**
I. Drywall Only			
Test number	7,8	6, 7, 11, 14, 15, 16, 17	18,19
Number of specimens	6	7	4
Test number for repair tests	N/A	14, 15, 16	N/A
II. Stucco Only			
Test number	20, 21	N/A	16, 17
Number of specimens	6	0	4
III. Drywall and Stucco			
Test number	N/A	N/A	14, 15
Number of specimens	0	0	4

2.1. The University of California, Irvine Test Programs

One can persuasively argue that a pivotal point in the beginning to better understand the performance of drywalls was the test program conducted at the University of California, Irvine under the auspices of the CoLA-UCI Light Frame Test Committee. This subcommittee of the Structural Engineers Association of Southern California was comprised of individuals from academia, the City of Los Angeles Department of Building and Safety, and practicing structural engineers. The subcommittee, chaired by Graeme Dick, defined a test program, commonly referred to as the CoLA Test Program, that was without precedence in scope and quality of test data. The reader is encouraged to read the excellent 2001 report typically referred to as the CoLA report (CoLA-UCI, 2001).

2.2. The CoLA Test Program at UCI

The CoLA test program documented the shear wall stiffness and strength as a function of the lateral displacement of the wall. The test program tested 36 groups of 8-foot by 8-foot shear walls with three samples in each group. Of these 36 groups only two of them were drywall only and are discussed in this section. The specifications for Test Groups 7 and 8 are shown in Table 4.

Table 4 Shear wall specifications for test groups 7 and 8

Group	Sheathing	Sill and Center Stud	Nail Type	Nailing Info
7	5/8 in. thick, GWB on both sides	2x4	1 7/8" drywall nails	4"/4" spacing; 3/8" edge distance
8	½ in. thick, GWB on both sides	2x4	1 5/8" drywall nails	7"/7" spacing; 3/8" edge distance

Both test groups were subjected to the revised TCCMAR fully reversing cyclic displacements as outlined and published by SEAOSC (1997).

Each shear wall was deformed to successively higher displacement levels and cycled to each displacement level three times before the FME was reached, and four times for demarcations beyond the FME. Figure 1 shows selected, because of this paper length, experimental data for Test 7A at two displacement thresholds.

The CoLA report defines a very important term, the Yield Limit State (YLS), as the point where the load difference between the first passage at a displacement and the third passage at a displacement is 5%. Figure 2 demonstrates the derivation of YLS from experimental data as explained in Appendix C of the CoLA report (2001). The first three cyclic fully reversing cycles were at 0.05-inch displacement and were essentially identical, thus are shown by a single loop in Figure 2. It is worth noting that consistent with the analysis results of Deierlein and Kanvinde (2003), Figure 2 shows a change in the load displacement curve after 0.05-inch (0.05% drift) response amplitude. Note that the 5% loss in strength and stiffness occurs between three and six cycles of response in the 0.05-inch to 0.10-inch displacement range (0.05% and 0.10% drift).

Figure 3 shows that as the wall undertakes its first passage up to 0.19-inch displacement there is a small loss of strength and stiffness. The shaded area in Figure 3 shows the energy lost between the first cycle where the wall reaches 0.19-inch displacement and the second time it reaches that displacement. The shaded area corresponds to about half of the energy available within the curves. This is a significant loss in energy capacity and, for example, if a second earthquake were to strike after the wall had already been subjected to 0.19-inch displacement once, the wall would have a lot less energy capacity to resist the second earthquake.

Figure 4 illustrates that once the wall goes to the 0.53-inch displacement three times, it only requires a 740 pound load to produce a wall displacement of 0.05 inches. This is a 60% loss of strength and stiffness when the wall has only been subjected to three cycles at 0.05-inch, three cycles at 0.19-inch, three cycles at 0.39-inch, one cycle at 0.53-inch, one cycle at 0.39-inch, one cycle at 0.19-inch, one cycle at 0.05-inch, and two cycles at 0.53-inch of loading.

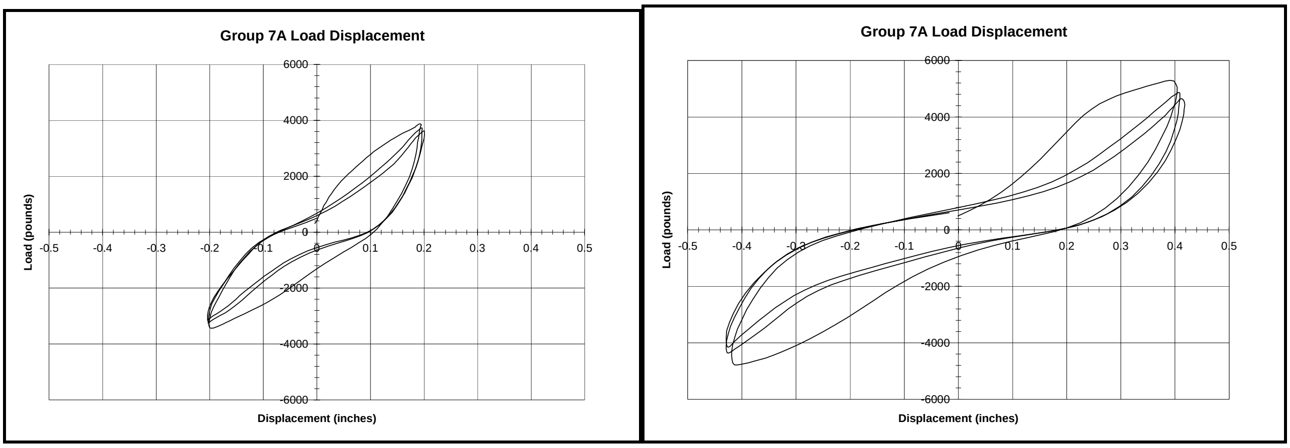

Figure 1 Three cycles of fully reversing load at 0.19- and 0.39-inch displacement

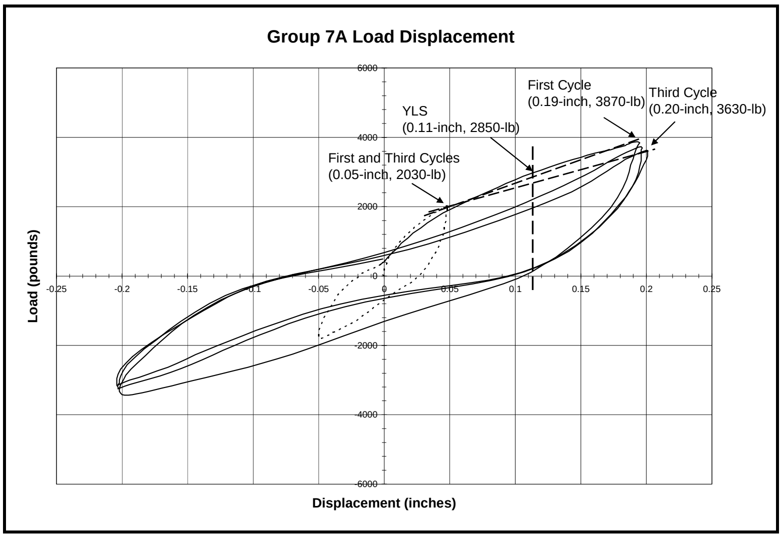

Figure 2 Calculation of YLS

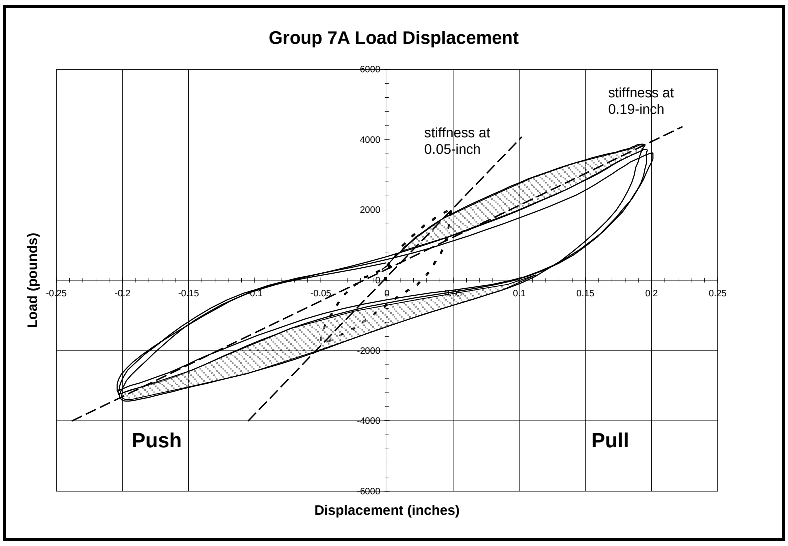

Figure 3 Loss of wall strength and energy capacity up to 0.19-inch displacement

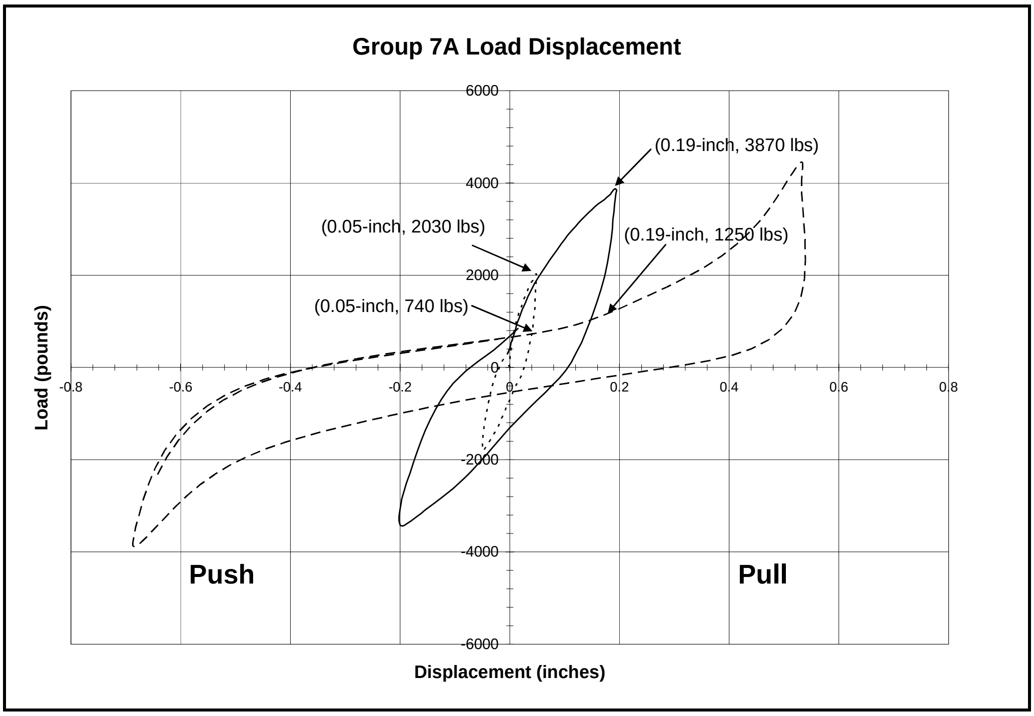

Figure 4 Loss of strength for repeated cycles of loading

Table 5 summarizes the strength loss between the first, second and third times Wall 7A goes through a specified displacement. As previously noted, at the 0.05-inch wall displacement level there is essentially no loss in load carrying capacity of the wall between the first to the third cycles. Next, note from Table 5 that where the wall is pulled to 0.19-inch for the first time (4th cycle total), it requires 3870 lbs where as the second time it only requires 3700 lbs to pull the wall to 0.19-inch, i.e. 4% loss in load. Carrying on, it follows that it requires only 3520 lbs to pull the wall to 0.19-inch the third time. Therefore, the third cycle at the 0.19-inch displacement requires 9% less load so stated differently, the wall has lost 9% of its stiffness from the first to the third time the wall goes to 0.19-inch. The pull load at 0.39-inch shows a larger loss in stiffness, i.e. 20% versus 9%. Note that similar conclusions apply to the push loads which result in a 13% and 19% loss in stiffness at 0.20-inch and 0.41-inch displacements, respectively. The other UCI tested wall showed the same behavior.

Table 5 CoLA Group 7A Original Wall Loss in Strength (lbs) between First, Second, and Third Times at Given Displacement Amplitude

Loading Phase	Displacement (inches)	1st time	2nd time	3rd time	loss 1 to 2	loss 2 to 3	loss 1 to 3
Pull	0.05	2030	2030	2030	0%	0%	0%
	0.19	3870	3700	3520	4%	5%	9%
	0.39	5290	4650	4220	12%	9%	20%
	0.53	5860	5300	4640	10%	12%	21%
	0.53	5300	4640	4410	12%	5%	17%
Push	-0.05	-1800	-1800	-1800	0%	0%	0%
	-0.20	-3440	-3140	-3010	9%	4%	13%
	-0.41	-4780	-4170	-3870	13%	7%	19%
	-0.66	-5170	-4680	-4080	9%	13%	21%
	-0.66	-4680	-4080	-3650	13%	11%	22%

Figure 5 displays the strength loss between the first and third passage through a given displacement as a percentage of strength loss for Test Groups 7 and 8, respectively.

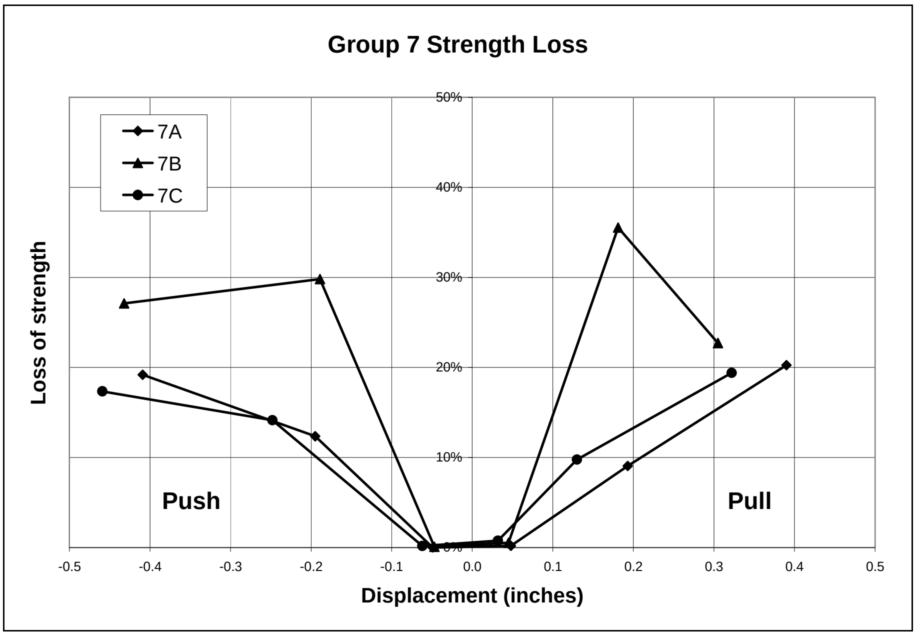

Figure 5 Percent strength loss experienced by the wall between first and third passage through a given displacement in Test Group 7

2.3. Testing and Analysis of One-Story and Two-Story Shear Walls at UCI

The test program at UCI documented the results of cyclic loading testing of one-story and two-story shear walls in CUREE report W-25 (Pardoen et al., 2003). The test program consisted of 26 groups of 16-foot by 8-foot one-story shear walls and 2 groups of 16-foot by 16-foot two-story shear walls with two identical samples each. Of these 28 groups only two of them were drywall only and are discussed in this section. The specifications for Test Groups 18 and 19 are shown in Table 6.

Table 6 Shear wall specifications for Test Groups 18 and 19

Group	Sheathing	Sill and Center Stud	Nail Type	Nailing info
18	GWB	2x4	1 1/4" long #6 screw	3 at 12 in. spacing
19	GWB	2x4	1 1/4" long #6 screw	6 at 12 in. spacing

The shear walls of report W-25 are double the width of the specimens used in the CoLA testing and each have an opening. The shear walls tested under Test Group 18 have a garage door opening of 9.75-foot by 7-foot. The shear walls tested under Test Group 19 have a pedestrian door opening of 3-foot by 6.75-foot.

Both test groups were subjected to the CUREE test protocol with fully reversing cyclic displacements as published in 2001 (Krawinkler et al.).

Table 7 collates the data collected in Test Group 18A in the UCI Test Program. Table 7 lists the maximum displacement for the pull and push phases of loading, respectively. The maximum displacement was calculated as the displacement at the maximum applied load for each cycle unless the maximum displacement attained in a cycle was 10% larger than the displacement corresponding to the maximum load. In such a case, the maximum displacement and its corresponding load were used.

Table 7 also summarizes the strength loss between the first, second, and third times the wall goes through a specified displacement. The loss values calculated as percentages clearly demonstrate the loss of lateral earthquake resistance due to damage to the shear walls. Again due to space limitation for this paper the other test results could not be presented but the performance was the same.

Table 7 CUREE W-25 Group 18A Original wall loss in strength (lbs) between first, second, and third times at given displacement amplitude

Loading Phase	Displacement (inches)	1st time	2nd time	3rd time	loss 1 to 2	loss 2 to 3	loss1 to 3
Pull	0.16	391	368	276	6%	25%	29%
	0.24	493	464	339	6%	27%	31%
	0.33	576	544	271	6%	50%	53%
	0.69	873	692	365	21%	47%	58%
	1.14	768	765	458	0%	40%	40%
	1.42	814	660	284	19%	57%	65%
	2.51	809	628	319	22%	49%	61%
	3.63	831	599	322	28%	46%	61%
Push	-0.15	-251	-294	-233	-17%	21%	7%
	-0.25	-304	-429	-319	-41%	26%	-5%
	-0.33	-473	-485	-291	-2%	40%	39%
	-0.69	-736	-650	-379	12%	42%	49%
	-1.08	-809	-675	-406	17%	40%	50%
	-1.49	-771	-662	-333	14%	50%	57%
	-2.47	-781	-615	-367	21%	40%	53%
	-3.80	-902	-773	-432	14%	44%	52%

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