Results from the city of Los Angeles-UC Irvine shear wall test program

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ABSTRACT

The Federal Emergency Management Agency (FEMA) and the California Office of Emergency Services (OES) has funded a timber shear wall test program to the City of Los Angeles. The test program is developing an understanding of the cyclic behavior of panels, especially wood panels, attached to wood framing by connectors such as nails or screws. One goal of this on-going experimental program has been to determine if the nailed shear wall systems can be modeled as principally shear deforming systems and to determine force-displacement relationships for commonly used nailed systems. Another significant goal of the test program has been to provide data for the improvement of design methods and to determine the adequacy of current codes or suggest code changes.

The experimental program is nearly 80% complete; 27 of the program's 35 shear wall configurations (with three samples per configuration) have been tested. The test program has been literally designed by various stakeholders in the project: researchers, practitioners and building officials. A major theme behind any test configuration has been to substantiate current building code practice and, if necessary, suggest code changes.

Numerical and graphical results from the test program have been disseminated to a wide audience via e-mail whereas a CD of the raw test data has been provided to those seeking more detailed information. The close coordination of the test program by its stakeholders has led to changes in the City of Los Angeles Building Code. Commencing in July 1999, the city's code has reflected changes from the experimental program that either confirm or modify the city's emergency '25% shear wall capacity reduction' implemented immediately following the 1994 Northridge Earthquake. It is anticipated that further code changes will result from the experimental program. Although the test program examines the behavior of many different sample configurations, this paper will only focus on the comparisons between similar tests of Structural I (Str I) grade plywood and Oriented Strand Board (OSB).

CITY OF LOS ANGELES – UCI SHEAR WALL TEST PROGRAM

The City of Los Angeles-UCI shear wall test program has investigated the size and spacing of fasteners, the type of sheathing as well as minor variations of the framing. Light gauge steel framing has been used in combination with plywood or OSB sheathing. The test program has included code-specified assemblies and connectors, including plywood, gypsum wallboard and stucco sheathing, thus verifying their adequacy or suggesting code revisions. Table 1 summarizes the 27 groups (from an eventual total of 35 groups) that have been completed as of January 2000.

While a substantial number of shear walls have been tested, the profession has suggested many shear wall configurations that have been beyond the project's scope. For instance, the program has only considered fully sheathed 2.44 m x 2.44 m walls using the test protocol recommended by the SEAOSC Ad-Hoc Committee on Cyclic Testing Standards [Shepherd, 1996]. This protocol uses displacement-controlled, fully reversing and multiple cycles to determine a stabilized stiffness. Shear walls longer or shorter than 2.44 m or shear walls with window or doorway cutouts have not been considered.

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Of particular interest to structural engineering practitioners has been the yield limit state and strength limit state summaries shown in Tables 2 and 3 respectively. These tables report the average values for the pull (+) and push (-) directions as well as the standard deviations. The yield limit and the strength limit states are defined in the next section.

Table 1 – City of Los Angeles / UC Irvine Shear Wall Test Matrix

Group	Sheathing Thickness / Mat'l / Application			Sill & Center Stud	Nail Type	Nail & Nailing Info (inches)					
						Size		Spacing		Edge Dist	
1	3/8	STR I	one side	3x4	8d hand driven common	2 1/2	.135	6	12	1/2	3/4
2	3/8	STR I	one side	3x4	8d hand driven common	2 1/2	.135	4	12	1/2	3/4
3	15/32	STR I	one side	3x4	10d hand driven common	3	.152	6	12	1/2	3/4
4	15/32	STR I	one side	3x4	10d hand driven common	3	.152	4	12	1/2	3/4
5	3/8	STR I	one side	2x4	8d hand driven common	2 1/2	.135	4	12	3/8	3/8
6	3/8	STR I	one side	2x4	8d hand driven common	2 1/2	.135	4	12	3/8	3/8
	1/2	GWB	both sides		1 5/8” drywall nails	1 5/8	.094	7	7	3/8	3/8
7	5/8	GWB	both sides	2x4	1 7/8” drywall nails	1 7/8	.094	4	4	3/8	3/8
8	1/2	GWB	both sides	2x4	1 5/8” drywall nails	1 5/8	.094	7	7	3/8	3/8
9	15/32	STR I	one side	3x4	10d hand driven common	3	.152	2	12	1/2	1/2
10	7/16	OSB	one side	3x4	8d hand driven common	2 1/2	.135	4	12	1/2	1/2
11	15/32	OSB	one side	3x4	10d hand driven common	3	.152	6	12	1/2	1/2
12	15/32	OSB	one side	3x4	10d hand driven common	3	.152	4	12	1/2	1/2
13	15/32	OSB	one side	3x4	10d hand driven common	3	.152	2	12	1/2	1/2
14	15/32	STR I	one side	LGS -1 5/8" flange	#8 Bugle Head Screws	1	.168	6	12	1/2	1/2
15	15/32	STR I	one side	LGS -1 5/8" flange	#8 Bugle Head Screws	1	.168	4	12	1/2	1/2
16	15/32	STR I	one side	LGS -1 5/8" flange	#8 Bugle Head Screws	1	.168	2	12	1/2	1/2
17	7/16	OSB	one side	LGS -1 5/8" flange	#8 Bugle Head Screws	1	.168	6	12	1/2	1/2
18	7/16	OSB	one side	LGS -1 5/8" flange	#8 Bugle Head Screws	1	.168	4	12	1/2	1/2
19	7/16	OSB	one side	LGS -1 5/8" flange	#8 Bugle Head Screws	1	.168	2	12	1/2	1/2
20	7/8	Stucco	one side	2x4	Furring Nail, 3/8 Head	1 3/8	.106	6	6	var	var
21	7/8	Stucco	one side	2x4	1" Crown Staples	7/8	.058	6	6	var	var
22	15/32	STR I	one side	3x4; field 2x's @ 24" o.c.	10d hand driven common	3	.152	4	12	1/2	1/2
23	15/32	STR I	horz	2x4 but 3x blocks	10d hand driven common	3	.152	4	12	1/2	1/2
24	15/32	STR I	one side	3x4; plywood bears @ sill	10d hand driven common	3	.152	4	12	1/2	1/2
25	3/8	STR I	one side	3x4	8d hand driven common	2 1/2	.135	2	12	1/2	3/4
26	15/32	STR I	one side	2x4	8d hand driven common	2 1/2	.135	4	12	3/8	3/8
27	3/8	STR I	one side	2x4; field 2x's @ 24" o.c.	8d hand driven common	2 1/2	.135	4	6	3/8	3/8

Table 2 – Yield Limit State of 2.44 m x 2.44 m Shear Walls

Group	Configuration Description		Nail Spacing		YLS Averages			YLS Standard Deviations				
					Drift (%)	Force(lbs)	lbs/ft	Drift (%)	Drift-cov	Force(lbs)	Force-cov	lbs/ft
1	3/8	STR I	6	12	0.32	3513	439	0.07	22%	575	16%	72
2	3/8	STR I	4	12	0.46	4970	621	0.01	3%	401	8%	50
3	15/32	STR I	6	12	0.26	3777	472	0.03	13%	257	7%	32
4	15/32	STR I	4	12	0.39	5451	681	0.09	23%	963	18%	120
5	3/8	STR I	4	12	0.42	4832	604	0.02	4%	262	5%	33
6	3/8	STR I	4	12	0.25	6183	773	0.05	21%	1021	17%	128
7	5/8	GWB	4	4	0.12	3037	380	0.05	43%	662	22%	83
8	1/2	GWB	7	7	0.08	1918	240	0.01	18%	138	7%	17
9	15/32	STR I	2	12	0.63	10124	1266	0.09	14%	1022	10%	128
10	7/16	OSB	4	12	0.25	4250	531	0.04	16%	480	11%	60
11	15/32	OSB	6	12	0.19	2906	363	0.05	24%	425	15%	53
12	15/32	OSB	4	12	0.26	5579	697	0.00	1%	303	5%	38
13	15/32	OSB	2	12	0.42	9672	1209	0.04	9%	628	6%	78
14	15/32	STR I	6	12	0.16	2513	314	0.01	7%	392	16%	49
15	15/32	STR I	4	12	0.17	3012	377	0.03	16%	396	13%	50
16	15/32	STR I	2	12	0.41	8707	1088	0.05	11%	614	7%	77
17	7/16	OSB	6	12	0.14	1949	244	0.02	13%	365	19%	46
18	7/16	OSB	4	12	0.13	2996	375	0.02	17%	300	10%	38
19	7/16	OSB	2	12	0.23	5834	729	0.09	40%	1537	26%	192
20	7/8	Stucco	6	6	0.08	1293	162	0.05	66%	492	38%	61
21	7/8	Stucco	6	6	0.03	862	108	0.02	57%	214	25%	27
22	15/32	STR I	4	12	0.43	6365	796	0.01	3%	377	6%	47
23	15/32	STR I	4	12	0.39	5929	741	0.05	14%	787	13%	98
24	15/32	STR I	4	12	0.37	6291	786	0.05	13%	820	13%	102
25	3/8	STR I	2	12	0.72	10788	1348	0.12	17%	1369	13%	171
26	15/32	STR I	4	12	0.47	5543	693	0.07	15%	446	8%	56
27	3/8	STR I	4	6	0.32	4693	587	0.04	13%	297	6%	37

Table 3 – Strength Limit State of 2.44 m x 2.44 m Shear Walls

Group	Configuration Description		Nail Spacing		SLS Averages			SLS Standard Deviations				
					Drift (%)	Force(lbs)	lbs/ft	Drift (%)	Drift-cov	Force(lbs)	Force-cov	lbs/ft
1	3/8	STR I	6	12	1.43	5470	684	0.14	10%	544	10%	68
2	3/8	STR I	4	12	1.87	7597	950	0.26	14%	481	6%	60
3	15/32	STR I	6	12	1.81	6748	843	0.33	18%	324	5%	41
4	15/32	STR I	4	12	1.97	9146	1143	0.22	11%	669	7%	84
5	3/8	STR I	4	12	1.26	6690	836	0.08	6%	455	7%	57
6	3/8	STR I	4	12	1.10	10368	1296	0.17	16%	438	4%	55
7	5/8	GWB	4	4	0.58	5554	694	0.10	18%	408	7%	51
8	1/2	GWB	7	7	0.37	3104	388	0.09	25%	248	8%	31
9	15/32	STR I	2	12	1.96	15177	1897	0.12	6%	556	4%	69
10	7/16	OSB	4	12	1.04	6082	760	0.18	17%	647	11%	81
11	15/32	OSB	6	12	0.96	4461	558	0.12	12%	240	5%	30
12	15/32	OSB	4	12	1.40	8507	1063	0.13	9%	152	2%	19
13**	15/32	OSB	2	12	1.80	15274	1909	0.11	6%	464	3%	58
14	15/32	STR I	6	12	1.61	7126	891	0.17	11%	292	4%	37
15	15/32	STR I	4	12	1.77	9775	1222	0.05	3%	248	3%	31
16	15/32	STR I	2	12	1.27	15172	1897	0.34	26%	1823	12%	228
17	7/16	OSB	6	12	1.48	5816	727	0.16	11%	305	5%	38
18	7/16	OSB	4	12	1.43	8522	1065	0.10	7%	621	7%	78
19	7/16	OSB	2	12	1.89	16031	2004	0.06	3%	353	2%	44
20	7/8	Stucco	6	6	0.64	2947	368	0.03	4%	153	5%	19
21	7/8	Stucco	6	6	0.57	2558	320	0.05	8%	73	3%	9
22	15/32	STR I	4	12	1.58	8837	1105	0.13	9%	532	6%	66
23	15/32	STR I	4	12	1.52	8956	1120	0.15	10%	497	6%	62
24	15/32	STR I	4	12	1.52	10110	1264	0.11	7%	546	5%	68
25	3/8	STR I	2	12	1.64	14209	1776	0.17	10%	1207	8%	151
26	15/32	STR I	4	12	1.26	7672	959	0.08	6%	348	5%	44
27	3/8	STR I	4	6	1.21	7110	889	0.10	9%	601	8%	75

YIELD/STRENGTH LIMIT STATES – FIRST MAJOR EVENT CONCEPT

The TCCMAR [Porter, 1987] sequentially phased displacement procedure introduced the concept of the First Major Event (FME) which has been defined as the first significant limit state that occurs during a test. A limit state is an event that signifies the demarcation between two behavior states. When a limit state occurs, some structural behavior of the event or system is altered. For instance, an FME occurs when the load capacity of the shear wall, upon recycling of the load to the same wall displacement increment, first drops noticeably from the original load and displacement.

The effect of the FME on wood-framed assemblies is not as pronounced as for concrete or masonry assemblies, where cracking or bond failures may result in a substantial change in the stiffness or strength of the assembly. For the wood-framed shear wall test samples in the City of Los Angeles-UCI program, the FME was estimated from the 'backbone' and 'degraded backbone' curves as shown in Figure 1. The 'backbone' curve represents the envelope of peak loads for the first cycle at a given displacement level whereas the 'degraded backbone' curve represents envelope of peak loads for the last cycle at the same displacement level.

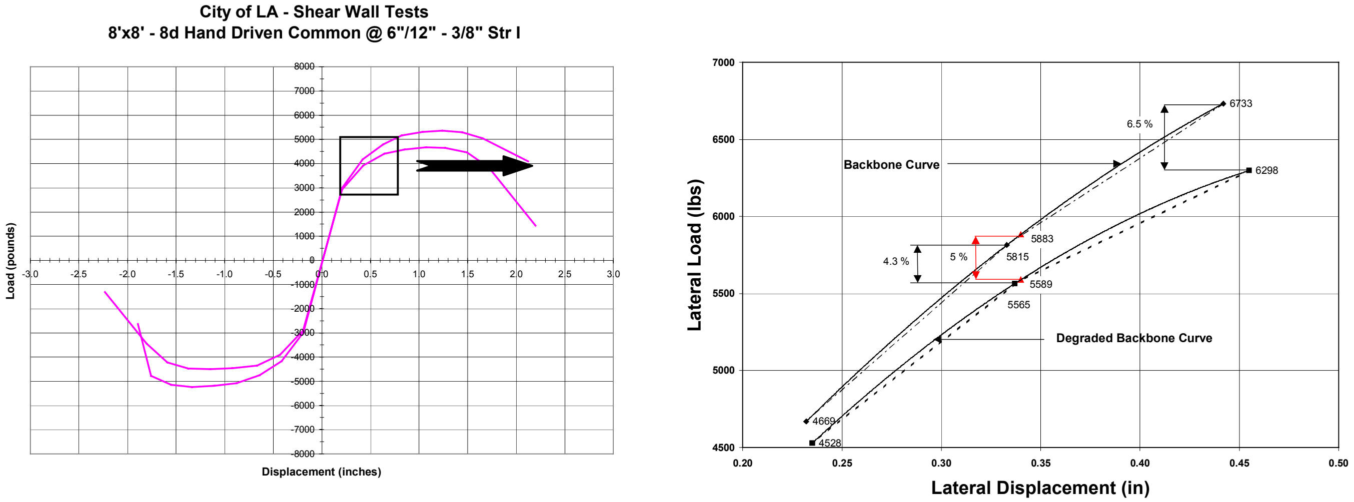

Figure 1 – Backbone & Degraded Backbone Curves for FME Calculation

As a rule, each shear wall is deformed to successively higher displacement levels, and is cycled to each displacement level three times before the FME is reached and four times for deformations beyond the FME. Before the FME is reached there is little difference in the force required to cycle the shear wall to a given displacement for each cycle. After the FME is reached, however, the force required to cycle the shear wall to a given displacement the last time is somewhat less than the force required to deform the shear wall the first time.

The definition adopted is that the Yield Limit State (YLS) or FME is reached when the force required to displace the sample the last time is 95% of the force required to displace the sample to the same level as the first time. The YLS is the point on the force-displacement diagram corresponding to the displacement and force reached on the first cycle to that displacement. Inasmuch as one of the relatively few data points that define the 'degraded backbone' curve (last excursion to a given displacement level) is likely to be exactly 95% of the 'backbone' curve (first excursion to a given displacement level), a parabolic curve fit process was adopted to determine the FME.

Consider the data in Figure 1b that corresponds to the 'windowed' curves shown in Figure 1a. Assume that the 'degraded backbone' curve is 95.7% of the 'backbone' curve at a given displacement level whereas the 'degraded backbone' curve is 93.5% of the 'backbone' curve at the next highest displacement level. Clearly the 'true' FME lies between these two pair of data points. By knowing the approximate FME level, one parabola is fit to three consecutive points on the 'backbone' curve (one point higher and two lower than the 'true' FME) and another parabola is fit to the three consecutive points on the 'degraded backbone' curve. It is a relatively routine procedure to then determine the displacement level corresponding to the point where the 'degraded backbone' curve is 95% of the 'backbone' curve.

The point of maximum force reached during the test defines the Strength Limit State (SLS). The SLS occurs at the maximum displacement for the maximum force attained. The force at the SLS need not be significantly higher than the force at the YLS, but for a ductile element or sub-system the displacement at the SLS will be a significant multiple of the displacement at the YLS. As noted earlier the YLS and SLS results are summarized in Tables 2 and 3.

DESCRIPTION OF TEST CONFIGURATION AND PROCEDURE

Test Program Characteristics

As of January 2000, the City of Los Angeles – UC Irvine timber shear wall test has completed 27 of the proposed 35 configurations. Three samples of each configuration were subjected to the SEAOSC test protocol for shear walls. As a rule, the framing for the 27 configurations have been 'similar' in construction, however, the framing for the six groups that comprise this study were identical. Each frame consisted of: a) two – 4" x 4" posts, b) one – 3" x 4" sill, c) one – 3" x 4" center stud, d) two – 2" x 4" top plates, and e) four – 2" x 4" field studs. The hold-downs were specially designed and fabricated from heavy gauge, 3-inch structural channel.

Test Setup

The shear wall samples were attached to the base of the test fixture with four 5/8-inch diameter anchor bolts. The bottom plate of the shear wall was supported on a 3 ½-inch wide by 96-inch long steel rectangular bar. This bar was set such that it only supported the framing of the walls. This allowed the sheathing panels to freely rotate when loading the shear wall laterally without the panels bearing on the test fixture at the bottom.

Anchor-bolt holes in the 3" x 4" sill were carefully located and pre-drilled using a drill jig to minimize bolt deformation and slip when the shear wall was laterally loaded in the plane of the wall. The diameters of the anchor-bolt holes in the sill were limited to a maximum of 1/16-inch oversize. Square steel plate washers, 1/8-inch thick by 2½-inches square, were used under the bottom plate bolts.

Racking shear loads were applied horizontally to the top of the shear wall test specimens through a steel H-beam lag-screwed (with 3/8-inch diameter lag screws spaced 6-inches on center) to the double top plate of the wall. The H-beam, in turn, was placed on a ¾-inch thick by 3-inch wide plywood spacer. The purpose of this spacer was to allow the sheathing panels to rotate when the shear wall was loaded laterally, without bearing on the H-beam at the top corners of the panels. The H-beam was restrained laterally (normal to the plane of the shear wall) by pairs of low-friction, Teflon pads fastened to the beam and to the adjacent steel bracing frames. This arrangement permitted in-plane displacement of the wall during the test while preventing the top of the wall from twisting outside of the load-application plane.

Racking shear loads were applied with a 55 kip capacity, programmable, double-acting hydraulic actuator (MTS Systems Corporation) that was bolted to a stiff vertical cantilever column hinged at the base to act as a lever arm. The hinged cantilever system was necessary to 'multiply' the actuator displacement, which was limited to 3-inches of stroke in the push and pull directions, to achieve greater displacement at the top of the wall. The horizontal load at the top of the wall was measured with a load cell in the horizontal plane of the top plate and steel H-beam.

Instrumentation

The seven data channels that were typically recorded during a shear wall test included the measurement of the -

- Horizontal-load between the shear wall and the hinged cantilever column
- Horizontal-displacement of the shear wall at the top plate
- Horizontal-displacement of the bottom plate relative to the test fixture (lateral in-plane sliding)
- Vertical-displacement at the bottom end of both end posts relative to the test fixture (uplift and compression)
- Vertical-displacement of the hold-down connectors relative to the end posts (displacement/bolt slip)

The horizontal load between the shear wall and the hinged cantilever column was measured with a Bonded Foil Type Strain Gage Load Cell, produced by Muse Measurements of San Dimas, CA. The load cell used for this test program was model SR-4-24K with a load rating of 24 kips @ 2.0024 mV/V.

The horizontal displacement of the shear wall at the top plate was measured using a PSCC Rayelco Position Transducer, otherwise known as a string potentiometer. Model P-20A (A246), having a position sensitivity of 51.01 mV/V/inch, was used for this test program. This voltage sensitivity corresponds to an accuracy of +/- 0.005 inch. The range of the potentiometer was 0-20 inches. To account for the cyclic displacements of the test protocol, the potentiometer was set to a displacement of approximately 10 inches at the beginning of each test.

The other five displacement measurements (sill slip, two post uplifts and two hold-down slips) were measured with Spring Return Linear / Position Sensor Modules (Precision Linear Potentiometers) produced by Duncan Electronics. Model 604 R4K potentiometers, having an accuracy of +/- 0.002 inches, were used to measure these five displacements.

Data Acquisition

Data sampling for all shear wall tests was taken with the Strawberry Tree data acquisition system. This system includes several components including the Strawberry Tree Data Acquisition software, the terminal panels, and the analog-to-digital transition hardware. The terminal panels were a mechanism to attach the various instruments' wiring to a more standard ribbon wire. This ribbon wire was, in turn, attached directly to the analog-to-digital boards within the computer system.

Data was acquired at 50 Hz (one data point every 0.02 seconds). Each data value from each instrument was placed in a data-logging array in columnar format. Between 5,000 and 10,000 data points were recorded for each channel.

COMPARISON OF SHEATHING RESULTS – OSB VS PLYWOOD

The principal goal in testing the six shear wall groups summarized in Table 4 was to observe the panel's behavior due to different sheathing materials and nail densities. Three shear walls were constructed for each of the following six configurations (listed as Groups 3, 4, 9, 11, 12 and 13) using hand-driven 10d common nails with a 1/2" edge distance on the sheathing:

Table 4 – Shear Wall Configurations for OSB/Plywood Comparison

G3 - 15/32" Str I plywood nailed at 6"/12"	G11 – 15/32" OSB nailed at 6"/12"
G4 - 15/32" Str I plywood nailed at 4"/12"	G12 – 15/32" OSB nailed at 4"/12"
G9 - 15/32" Str I plywood nailed at 2"/12"	G13 – 15/32" OSB nailed at 2"/12"

Results and Observations

The strength and drift results for this collection of shear wall tests are summarized in Table 5. If the mean values are considered for each test group, then the following observations can be made:

Table 5 – YLS and SLS Results for OSB/Plywood Shear Walls

Group	Configuration Description			YLS Averages			SLS Averages		
				Drift (%)	Force (lbs)	lbs/ft	Drift (%)	Force (lbs)	lbs/ft
3	15/32	STR I	6"/12"	0.26	3777	472	1.81	6748	843
4	15/32	STR I	4"/12"	0.39	5451	681	1.97	9146	1143
9	15/32	STR I	2"/12"	0.63	10124	1266	1.96	15177	1897
11	15/32	OSB	6"/12"	0.19	2906	363	0.96	4461	558
12	15/32	OSB	4"/12"	0.26	5579	697	1.40	8507	1063
13	15/32	OSB	2"/12"	0.42	9672	1209	1.80	15274	1909

- Nail density increases YLS nearly linearly
  - 6"/12" to 4"/12" (1.5x) increases YLS by 1.68x
  - 4"/12" to 2"/12" (2.0x) increases YLS by 1.80x
  - 6"/12" to 2"/12" (3.0x) increases YLS by 3.01x
- Nail density increases SLS nearly linearly
  - 6"/12" to 4"/12" (1.5x) increases SLS by 1.63x
  - 4"/12" to 2"/12" (2.0x) increases SLS by 1.73x
  - 6"/12" to 2"/12" (3.0x) increases SLS by 2.84x

- For more densely nailed panels, OSB YLS nearly matches Plywood YLS (102%, 96%)
- For more densely nailed panels, OSB SLS nearly matches Plywood SLS (93%, 101%)
- For lightly nailed panels (6”/12”), OSB YLS is significantly lower than Plywood YLS (77%)
- For lightly nailed panels (6”/12”), OSB SLS is significantly lower than Plywood SLS (66%)
- Plywood drift capacity is relatively insensitive to panel nail density (1.80%, 1.96%, 1.97%)
- OSB drift capacity is very sensitive to panel nail density (0.96%, 1.40%, 1.80%)

Summary

The experimental results to date from a test and analysis program have been reported. These results suggest that Plywood and OSB correlate well for more densely nailed panels, but for lightly nailed panels, OSB has significant strength reductions. OSB also tends to have lower drift capacity than similar plywood panels, with lightly nailed OSB panels having severe capacity reductions. Panels also tend to behave in a nearly linear fashion with regard to nail density.

CONCLUSIONS

Clearly reporting the results of a test program that has considered 27 different configurations is beyond the scope of one technical paper. While the comparison of six configurations with identical framing but different sheathing and nailing schedules has been presented, there are many other comparisons that can (and will) be made during the final phase of the test program. Stucco and gypsum wall board performance, light gage steel framing, OSB vs. plywood, perimeter and field nail density, stud spacing, center stud size, edge nailing distance, etc. are just some of the anticipated investigations.

One study underway is the definition of the YLS and how its value is affected by using ‘degraded backbone curve value / backbone curve value’ ratios of 95% (the current standard) versus, say, 93% and 90% standards. Additionally, a YLS based solely on the backbone curve is being investigated. Despite these ongoing studies, it may be of interest to report some recent (and preliminary) YLS/SLS observations of the data by APA [Rose, 2000]. The calculated the ratio of YLS to SLS from City of Los Angeles / UC Irvine data summaries given in Tables 2 and 3 provide the following observations of the YLS/SLS ratio:

1. Wood structural panel sheathing/wood framing (17 sets, 51 tests) has an average value of 0.66 and is quite consistent. A value of 0.65 is suggested.

2. Wood structural panel sheathing/steel framing (6 sets, 18 tests) is quite consistent and has an average value of 0.38 or 0.34 if one outlier (Group 16) is excluded. A value of 0.35 is suggested.

3. Gypsum wallboard/wood framing (2 sets, 6 tests) has an average value of 0.59. A value of 0.60 is suggested.

4. Stucco/wood framing (2 sets, 6 tests) has an average value of 0.44 for the nailed configuration and an average value of 0.32 for the stapled configuration. A value of 0.45 is suggested for the nailed configuration whereas a value of 0.33 is suggested for the stapled configuration.

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