SHEATHING NAIL BENDING-YIELD STRESS: EFFECT ON CYCLIC PERFORMANCE OF WOOD SHEAR WALLS

Erin N. Anderson[1]
Graduate Research Assistant

Robert J. Leichti[2]
Professor
Department of Wood Science and Engineering
Oregon State University
Corvallis, OR 97331

Edward G. Sutt, Jr.
Engineering Manager, Fastener Technology
Stanley Fastening Systems, LP
East Greenwich, RI 02818

and

David V. Rosowsky
Department Head and A.P. and Florence Wiley Chair
Zachry Department of Civil Engineering
Texas A & M University
College Station, TX 77843

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ABSTRACT

This study investigated the effects of sheathing nail bending-yield stress (f_{yb}) on connection properties and shear wall performance under cyclic loading. Four sets of nails were specially manufactured with average f_{yb} of 87, 115, 145, and 241 ksi. Nail bending-yield stress and the hysteretic behavior of single-nail lateral connections were determined. The parameters of the lateral nail tests were used in a numerical model to predict shear wall performance and hysteretic parameters. The competency of the numerical model was assessed by full-scale cyclic tests of shear walls framed with Douglas-fir lumber and sheathed with oriented strandboard (OSB). The parameters of the shear wall model were used in another program to predict shear wall performance for a suite of seismic ground motions. The single-nail connection tests and wall model computations suggested that increased f_{yb} of the sheathing nails should lead to improved wall stiffness and capacity. In both single-nail lateral connection and shear wall tests, the probability of nonductile failure modes increased as f_{yb} increased. The peak capacity of the walls increased as f_{yb} of the sheathing nails increased up to 145 ksi, but wall initial stiffness, displacement at peak capacity, and energy dissipation were not significantly affected by f_{yb}. Sheathing nail f_{yb} greater than 145 ksi did not enhance the overall cyclic behavior of wood shear walls.

Keywords: Wood, nails, bending-yield stress, cyclic tests, shear walls, models, CASHEW.

INTRODUCTION

Shear walls are a main part of the lateral-load-resisting system in light-frame wood buildings. The connections, such as sheathing nails, in the shear walls provide ductility, damping, and energy dissipation through mechanisms such as internal friction, unrecoverable damage, connection failure, and yielding of the metal fasteners (Chui et al. 1998; Lam et al. 1997). Altering the initial stiffness, resistance, or energy dissipation capacity of a lateral-load-resisting system can affect the performance of a structure (Shenton et al. 1998). An extensive body of literature devel-

[1] Current address: Project Engineer, DCI Engineers, 3120 Colby Ave., Suite 100, Everett, WA 98201.

[2] Current address: Senior Compliance Engineer, Stanley Fastening Systems, L.P., East Greenwich, RI 02818 (corresponding author).

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oped since the 1950s describes the role of nail spacing and other construction variables, such as exterior sheathing, framing, openings, and hold-downs, on the performance of shear walls.

The sheathing-framing connections govern the behavior of the shear wall; therefore, altering the properties of the nail or the wood materials could modify the behavior of the shear wall. It is logical to hypothesize that increasing the bending-yield stress (f_{yb}) of the sheathing nails would improve shear wall performance. The main objective of this study was to assess the effect of f_{yb} of the sheathing nails on shear wall performance. Specific objectives included

- evaluating the laterally loaded single-nail connections with a range of nail f_{yb} values
- experimentally evaluating shear walls where the sheathing nail f_{yb} is the source of variation
- numerically evaluating probable performance of shear walls representing a range of nail f_{yb} values for a suite of seismic ground motions.

BACKGROUND

A contemporary wood shear wall consists of four main parts: engineered structural panels, such as plywood or oriented strandboard (OSB); a wood stud frame; nails connecting the panels to the stud frame; and the foundation, including anchorage bolts and devices. The weakest links in a structure are often the connections (Kalkert and Dolan 1997); therefore, the key to predicting the overall system response numerically is successfully modeling the hysteretic behavior of the nails (Foliente 1995). The essential parameters, including initial stiffness K_0, peak wall capacity (P_{max}), and deflection at peak capacity (ΔP_{max}), can be extracted from the load-displacement curves (Dolan and Madsen 1992b; Filiatrault 1990; Gupta and Kuo 1985; McCutcheon 1985).

Wood shear walls have gained a reputation for being highly resistant to earthquakes because of the high strength-to-weight ratio of wood and the ductility of connections (Filiatrault 1990). Damage to wood buildings in the Northridge and Loma Prieta earthquakes prompted further investigation of cyclic load effects in shear walls and connections. The California Universities for Research in Earthquake Engineering Caltech (CUREE) Woodframe project examined the performance of wood-frame buildings and their connections in earthquake-prone regions and developed the CUREE loading protocol (Krawinkler et al. 2000). The protocol was initially devised for shear walls, but it also has been used to evaluate individual nail and staple connections (Jones and Fonseca 2002; Kent 2004).

Nails are one of the most common fasteners in structural timber construction and wooden assemblies (Aune and Patton-Mallory 1986b). European Yield Model (EYM) (Aune and Patton-Mallory 1986 a,b; Johansen 1949; Larsen 1973; Moller 1950; Wilson 1917) is the common method for design of laterally loaded dowel-type fasteners. The EYM analysis is based on the embedment strength of the wood, the f_{yb} of the dowel, and the joint geometry (AF&PA 2005). The yield modes of laterally loaded connections involve nail bending, wood crushing, or a combination of the two. Four post-yield failures, however, are characteristic for sheathing-framing connections (Lattin 2002): withdrawal, fatigue, pull-through, and edge tear-out. These are observed mostly in post-peak loading. Nail fatigue is not common in earthquake damage (He et al. 1998; Langlois et al. 2004; Rose 1999; Salenikovich and Dolan 2003).

Typically, the sheathing thickness is increased or the nail spacing is decreased to increase the design capacity of a shear wall. Both design strategies have limitations because panels can be manufactured to only certain thicknesses, and nail spacing decreases are limited. Langlois (2002) and Lattin (2002) found that altering the failure modes of the sheathing connections can improve the performance of the shear wall. Both studies found that nail withdrawal was the dominant failure mode of connections when smooth shank nails were used. When ring-shank nails were used, however, the dominant failure mode changed. Langlois found that the shear wall ultimate static strength could be increased by 40%

using 0.113-in.[1]-diameter annular ring-shank nails, and the dominant failure modes switched to pull-through, followed by fatigue. Lattin used a variety of nails, including sheathing nails that were partially annularly threaded and had a large diameter head; the ultimate capacity of a cyclically loaded shear wall with a sheathing nail diameter of 0.113 in. increased in this study also. The dominant failure modes were pull-through and fatigue. The percentage of pull-through failures remained approximately the same as with smooth-shank nails because the large nail head counteracted the additional pull-through forces created by the superior withdrawal resistance or the ring shank, and the nail fatigue also increased as a result of the decrease in withdrawal failure.

Even though the f_{yb} of a nail affects the lateral design properties of an individual connection, it does not affect withdrawal capacity. Changing the f_{yb} of the sheathing nail may change the expected yield mode of a single-fastener connection, yet it is not known if the sheathing nail f_{yb} is well correlated to shear wall performance.

When a wall or nail connection is subjected to cyclic loading, the load-displacement curve is a series of pinched hysteresis loops in which each successive loop has a degrading stiffness (Dolan and Madsen 1992b; Foliente 1995). At small displacements, a nail connection behaves elastically. At large displacements, however, the connection behavior is inelastic and nonlinear without a distinct yield point (Filiatrault 1990), which makes hysteretic response of the connection difficult to predict. The positive quadrant hysteretic behavior can be captured with ten extracted parameters to fully describe one connection (Foliente 1995). Five parameters (K_0, initial stiffness; r_1, secondary stiffness factor; F_o, y-intercept for asymptotic line; r_2, post-ultimate capacity stiffness factor; Δ_u, displacement at ultimate load) describe the envelope response of a connector (Dolan and Madsen 1992a; Foschi 1974); the other five (r_3, unloading stiffness factor; r_4, pinching stiffness factor; F_1, y-intercept for zero displacement; α, stiffness degradation factor; β, strength degradation factor) describe the hysteretic part of the response resulting from cyclic loading (Fonseca et al. 2002). The hysteretic parameters are illustrated and described by Folz and Filiatrault (2001) where the reader is directed for more background. The ultimate capacity from shear wall testing (P_{max}) and the same factor from models (F_u) are also used as performance indicators. A complete nonlinear load-slip curve provides information about the ultimate load, initial stiffness, unloading stiffness, post-peak stiffness, ductility, and residual deformation after unloading (Foschi and Bonac 1977), as well as the degrading factors. The hysteretic response and essential parameters of a shear wall can be predicted from the hysteretic characteristics of individual sheathing-framing nailed joints with similar properties and boundary conditions (Foliente 1995; Folz and Filiatrault 2001).

In the past, the capacity of cyclically loaded shear walls has been determined by experimentation, and by numerical modeling. Finite-element analysis models have been developed for nailed joints (Chui et al. 1998; Hunt and Bryant 1990; Ni and Chui 1996) and shearwalls (Cheung et al. 1988; Gupta and Kuo 1985; Itani and Fridley 1999; Kasal and Leichti 1992; Kasal et al. 1994; Polensek 1976). Finite-element analysis can be accurate and can utilize nail behaviors, but finite-element models are often computationally cumbersome particularly with heterogeneous orthotropic materials.

Finite-element models used in conjunction with other numerical models are capable of the type of calculations necessary to predict cyclic responses of large systems (Dolan and Foschi 1991; Gupta and Kuo 1985; Itani and Cheung 1984; Polensek and Schimel 1985; White and Dolan 1995). A recent numerical model, Cyclic Analysis of SHEar Walls (CASHEW) (Folz and Filiatrault 2000, 2001), takes into account many aspects of the previous models and principles of nonlinear hysteretic nail responses without finite-element analysis. CASHEW calculates the wall response based on the load-slip characteristics of the nail connections, the wall geometry,

[1] SI Units: 1 inch = 25.4 mm, 1 lbf = 4.45 N, 1 ksi = 6.9 MPa, 1 lbf · in = 0.113 N · m

shear modulus of the sheathing, and nail locations. The response is described by the ten hysteretic parameters for the typical sheathing-framing connection in the wall. Others have evaluated the effect of nail geometry—for example, shank characteristics (Langlois 2002, Lattin 2002) or head shape (Lattin 2002)—on the performance of the connection. Presumably, performance of the wall assembly could also be modified by changing the strength of the nail. Our thorough search of the literature did not identify engineering information that revealed the effect of nail f_{yb} on the cyclic performance of laterally loaded connections of wood frame shearwalls.

MATERIALS AND METHODS

Stanley Bostitch® (East Greenwich, RI) manufactured nails with four characteristic f_{yb} values: 87 ksi, 115 ksi, 145 ksi, and 241 ksi. The nails were 0.113 in. in diameter and 2⅜ in. long with a full round head and smooth shank. Table 1 summarizes the test results establishing actual nail f_{yb} (Anderson 2005; ASTM 2003). The 87-ksi nail did not comply with ICC (2006), which requires nails with a diameter less than 0.15 in. to have an average f_{yb} not less than 100 ksi.

The building materials were stud grade Douglas Fir-Larch and 7⁄16-in. oriented strandboard (OSB) sheathing (Exposure 1) with average moisture contents of 8.7% and 7.1%, respectively. The moisture contents were measured in accordance with D 4444 (ASTM 2005a). The average embedment strengths, found in accordance with D 5764 (ASTM 2005b), were 5380 psi for the lumber and 5400 psi for the sheathing.

The EYM equations given in the National Design Specification (AF&PA 2005) were used to determine the expected design yield mode for the single-shear specimens built with these materials. The observed yield mode for each type of nail also was found to be Mode III_s: a plastic hinge forming in the OSB, along with some crushing of the OSB. The yield mode calculations (Table 2) also showed Mode III_s to be the expected design yield mode for the nail connections, regardless of nail f_{yb}.

Single-fastener connection tests

The standard single-nail connection test configuration was an 8-in. piece of framing and a 4- × 6-in. piece of OSB sheathing nailed together with a single fastener while maintaining a minimum edge distance of 2 in. for the end and edges. The apparatus for the connection tests kept the specimen straight and in plane to reduce eccentricities caused by nail withdrawal. At first, two monotonic tests at a constant loading rate of 0.20 in./min were conducted for each nail type in order to determine a reference displacement used to scale the cyclic test protocol for each nail type (Anderson 2005; ASTM 2002; Kent 2004). Based on the results of the monotonic tests (Table 3), a reference displacement of 0.5 in was selected.

Twelve single-nail connection specimens from the undamaged materials of each shear wall specimen and having the same configuration and set-up as the monotonic tests were tested cyclically at 0.2 Hz. The hysteretic parameters of the cyclic single-nail connection

TABLE 1. *Nail bending-yield strength, f_{yb}, expressed as mean (SD) from tests in accordance with F 1575 (ASTM 2003) (nail diameter 0.113 in., length 2⅜ in., n = 24).*

Nail f_{yb} (ksi)	
Nominal	Actual
87	85.0 (6.34)
115	115.4 (3.62)
145	144.6 (5.75)
241	240.9 (4.46)

TABLE 2. *Calculated reference capacity (Z) for laterally loaded single-nail connections constructed with Douglas Fir-Larch and 7⁄16-in. OSB sheathing with nails having different f_{yb}. Controlling yield mode is Mode III_s for these materials and connection configuration.*

	Z (lbf)			
Yield mode	87 ksi	115 ksi	145 ksi	241 ksi
III_s	60	65	71	87

TABLE 3. *Single-fastener connection monotonic test results by nail f_{yb}.*

Sheathing nail f_{yb} (ksi)	Test	K_0 (lbf/in.)	P_{max} (lbf)	Δ at P_{max} (in.)	P_{yield} (lbf)	Ref Δ (in.)
87	1	3,432	258	0.44	96	0.616
	2	6,555	296	0.47	127	0.766
	Mean	4,994	277	0.45	112	0.691
115	3	8,514	337	0.36	137	0.780
	4	14,218	370	0.37	185	0.740
	Mean	11,366	353	0.36	161	0.760
145	5	7,326	374	0.62	119	0.421
	6	6,784	367	0.60	128	0.398
	Mean	7,055	371	0.61	124	0.410
241	7	9,467	492	0.82	66	0.484
	8	11,129	379	1.04	112	0.420
	Mean	10,298	436	0.93	89	0.452

tests were determined with the software program SASHFIT (Elkins and Kim 2003a) and were used in the shear wall models.

Analysis of variance was conducted with tests of significance ($\alpha = 0.05$) for the ten hysteretic parameters. The analysis of variance was for a completely random design where nail f_{yb} was the treatment source of variation.

Shear wall tests

Eight 8- × 8-ft shear walls fully anchored with hold-downs were constructed with the framing for each wall spaced 16 in. on center. The nails with different f_{yb} values were used only for the sheathing attachment; the framing nails were typical construction nails. For each nail type, two walls were tested. The sheathing nails were spaced at 4 in. on the perimeters and 12 in. in the field of each panel. The minimum edge distance was ⅜ in. The plate-to-stud connection was end-nailed with two 16d common nails; the double top plates were connected with one 3½ × 0.162 in. (16d common) nail every 6 in. The double end studs were connected with two 3 × 0.148 in. (10d common) nails every 8.5 in. except where hold-downs were located (the bottom 13 in. of the end studs).

The walls were tested in accordance with E 2126 (ASTM 2002) according to Method C (CUREE loading protocol). Rather than testing a wall monotonically to determine the reference displacement, we selected the reference displacement on the basis of previous studies by Langlois (2002), Lattin (2002), and Salenikovich and Dolan (2003) and the limits of the testing equipment. To maximize the possibility of post-yield behavior, a reference displacement of 3 in. was used. The quantitative wall performance parameters were initial stiffness (K_0), maximum capacity (P_{max}), displacement at maximum capacity (ΔP_{max}), energy dissipation (energy), and ductility.

Analysis programs

The average nail hysteretic parameters were used as input for CASHEW (Folz and Filiatrault 2000, 2001), a program that uses the geometry of a shear wall, along with the connection hysteresis parameters, to predict the load-displacement response and energy dissipation of the shear wall under a user-defined loading. CASHEW governs global hysteretic parameters for the cyclic response of the entire wall as output. The wall hysteretic parameters are then used as input to the program SASH1 (Elkins and Kim 2003b). This program performs dynamic time history analysis of a wood shear wall, modeling the wall as a nonlinear single-degree-of-freedom system.

The SASH1 analysis uses an input earthquake ground motion record. The records considered in this study included 20 earthquakes from the Los Angeles area characteristic of non-near fault ground motions. Each record was scaled such that its mean 5% damped spectral value between periods of approximately 0.1 and 0.6 seconds matched the design spectral value for the same period range. The spectral value was matched to 1.1 g for the life safety (LS) limit state, also defined as a 10% in 50 years (10/50) hazard level (FEMA 2000). The spectral design value is matched to 0.633 g for the immediate occupancy (IO) hazard level, defined as a 50% probability of occurrence in 50 years (50/50) by FEMA. Seismic zone 4 and soil type D (Site Class D under IBC 2006) were assumed for both hazard levels. Rosowsky and Kim (2002) give further

TABLE 4. *Average (COV) hysteretic nail parameters for lateral single-nail connection specimens from SASHFIT, Standard & Better Douglas Fir-Larch and 7/16-in. OSB where n is the number of replicates.*

Sheathing nail f_{yb} (ksi)	n	K_0 (lbf/in.)	r_1	r_2	r_3	r_4	F_0 (lbf)	F_1 (lbf)	Δ_u (in.)	α	β	F_u (lbf)
87	24	2574	0.050	–0.066	4.36	0.012	237	31.1	0.424	0.244	1.18	296
		(0.19)	(0.72)	(0.65)	(0.18)	(0.22)	(0.22)	(0.05)	(0.15)	(0.40)	(0.09)	(0.19)
115	24	2851	0.037	–0.069	3.91	0.028	249	32.4	0.425	0.265	1.15	287
		(0.12)	(0.50)	(0.61)	(0.14)	(0.36)	(0.14)	(0.09)	(0.22)	(0.31)	(0.09)	(0.11)
145	24	2866	0.051	–0.075	4.43	0.041	261	29.2	0.402	0.244	1.13	314
		(0.11)	(0.38)	(0.69)	(0.17)	(0.45)	(0.17)	(0.15)	(0.10)	(0.44)	(0.06)	(0.14)
241	21	3099	0.057	–0.051	4.77	0.064	305	28.7	0.401	0.158	1.08	358
		(0.12)	(0.53)	(0.41)	(0.13)	(0.72)	(0.14)	(0.12)	(0.30)	(0.47)	(0.23)	(0.12)

information on the procedure for characterizing seismic hazard.

RESULTS AND DISCUSSION

Single-fastener connection tests

Ten hysteretic parameters and the ultimate capacity (F_u) were extracted for every single-fastener connection test (Table 4). As a result of the f_{yb} of the sheathing nails, the single-nail connections had a significant difference-the initial stiffness (K_0) ($p = 0.0022$) and the F_u ($p \ll 0.001$). The K_0 was increased by 30% as the nail f_{yb} ranged from 115 ksi to 241 ksi. Ultimate capacity, however, increased by approximately 26% when the nail f_{yb} increased from 115 ksi to 241 ksi. Thus, a two-fold increase in sheathing nail f_{yb} translated to roughly a 30% improvement in capacity and stiffness of the single-nail connection. The displacement at peak capacity was similar for each nail f_{yb} ($p = 0.952$). The other hysteretic parameters were not evaluated by ANOVA.

Nail withdrawal was the dominant connection failure (>50% of failures) for all four nail types (Table 5). The percentage of fatigue failures increased, however, as nail f_{yb} increased.

TABLE 5. *Percentage of nail failures for lateral single-nail connections and shear walls by nail f_{yb} value.*

Test	Nail f_{yb} (ksi)	Nail failure (%) Withdrawal	Pull-through	Fatigue	Tear-out
Single-nail	87	75	8	17	0
	115	71	8	21	0
	145	67	8	25	0
	241	55	0	45	0
Shear wall[a]	87	80	12	7	1
	115	65	28	7	0
	145	49	39	10	2
	241	42	32	24	2

[a] Perimeter nails only, field nails not considered.

Shear wall tests

In order to characterize the behavior of the walls constructed with a given nail type, the backbone curves were defined by averaging the results from the two shear walls with the same fasteners (Fig. 1). The values of P_{max} for the 145-ksi and the 241-ksi shear walls (Table 6),

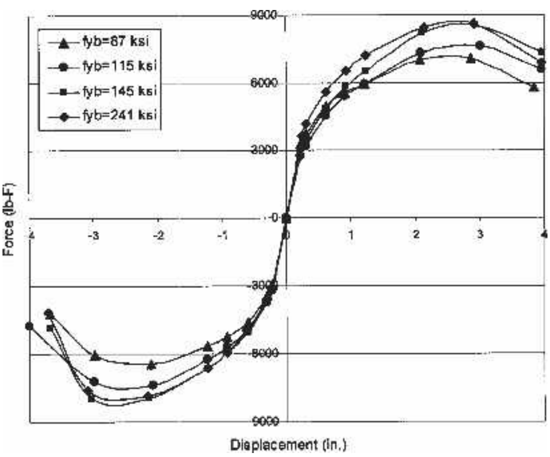

FIG. 1 Average backbone curves for the tests of two walls for each sheathing nail bending-yield strength (f_{yb}) value.

TABLE 6. *Summary of cyclically tested 8- × 8-ft. shear wall results for each nail bending-yield strength (f_{yb}).*

Sheathing nail f_{yb} (ksi)	Wall test	K_0 (lbf/in.)	P_{max} (lbf)	Δ at P_{max} (in.)	Energy (kip · in.)	Ductility
87	1	11,211	6999	2.84	131	9.18
	2	12,320	7155	2.11	124	9.43
	Mean	11,760	7077	2.48	128	9.30
115	3	9,856	7393	2.95	131	9.71
	4	11,774	7846	2.99	142	9.75
	Mean	10,815	7619	2.97	136	9.73
145	5	12,478	8656	2.87	147	9.34
	6	9,753	8501	2.91	147	9.68
	Mean	11,115	8578	2.89	147	9.56
241	7	11,190	8871	3.05	143	9.77
	8	12,256	8345	2.94	135	9.08
	Mean	11,723	8608	3.00	139	9.42

were similar ($\alpha = 0.01$), and the P_{max} values for the 87-ksi and 115-ksi walls were similar and significantly lower than those of the 145-ksi and 241-ksi walls.

The range of the displacement at P_{max} (Table 6) indicates that nail f_{yb} did not influence this parameter. Also, no significant differences ($p = 0.104$, $\alpha = 0.05$) were found in the cumulative energy dissipated by the different walls (Fig. 2). At primary cycle 7, which is the cycle of peak displacement, the 87-ksi walls had the lowest cumulative energy dissipated (94,400 lb·in.), while the 145-ksi walls had the highest (102,000 lb·in.), an 8.6% difference.

The K_0 values, which are based on the ascending branch of the first primary cycle between 10% and 40% of the maximum load, were statistically similar (Table 6), indicating that sheathing nail f_{yb} did not affect the initial stiffness of the shear wall assembly.

The dominant assembly failure mode in the wall tests was the sheathing pulling away from the framing at the center stud and elsewhere at the sheathing perimeters. The studs also pulled away from the bottom plate post-peak. Typically, the end studs separated from the top plate at large displacements.

Four modes of failure were observed for the

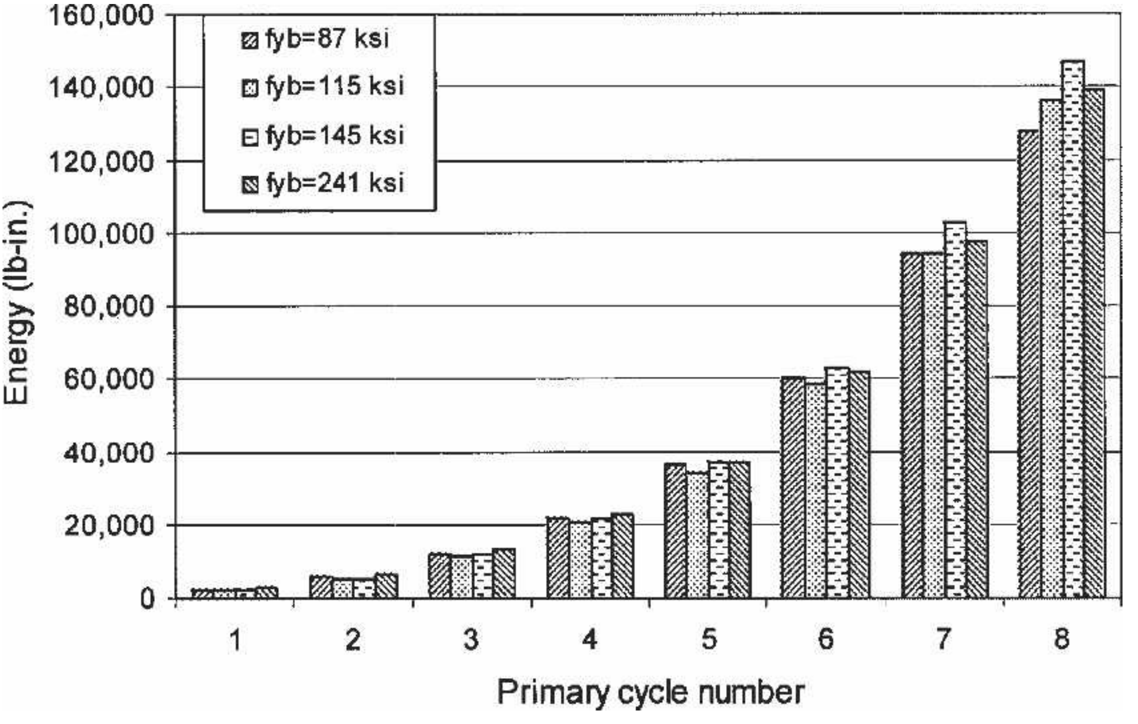

FIG. 2 Average cumulative energy dissipated at the primary cycles for the two walls at each bending-yield strength (f_{yb}) value.

TABLE 7. *Hysteretic parameters (n = 1) from CASHEW for modeled shear walls.*

Sheathing nail f_{yb} (ksi)	K_0 (lbf/in.)	r_1	r_2	r_3	r_4	F_0 (lbf)	F_1 (lbf)	Δ_u (in.)	α	β	F_u (lbf)
87	11,330	0.033	−0.077	2.89	0.181	7950	962	2.10	0.307	1.164	8,311
115	12,565	0.017	−0.084	2.62	0.416	8392	1042	2.08	0.336	1.130	8,444
145	12,420	0.028	0.089	2.83	0.058	8974	981	2.02	0.327	1.110	9,088
241	12,690	0.022	−0.578	2.93	0.077	1098	989	2.05	0.374	1.070	10,482

perimeter sheathing nails: withdrawal, pull-through, fatigue, and tear-out. Similar to the single-nail connection tests, the dominant failure mode in the walls was withdrawal for all nail types. As the nail f_{yb} increased, the percentage of nails failing from pull-through or fatigue also increased (Table 5). The higher f_{yb} nails were more likely to have nonductile failures in the shear wall tests; the pattern also was evident in the single-fastener tests (Table 5). Tear-out was not a common mode of failure, since the minimum edge distance was at least ⅜ in., but did occur at the corners of the sheathing and along the center stud. These failure results parallel those reported by Lattin (2002).

The overall ductility of the walls (displacement at P_{max}/yield displacement) was not affected by nail f_{yb}, even though the higher f_{yb} nails had more nonductile failures. The 115-ksi walls had the highest average ductility (9.7). The average ductility of the other walls ranged from 9.3 to 9.6, with the 87-ksi walls being the lowest and the 145-ksi walls, the highest. Thus, nail f_{yb} was not correlated with wall ductility.

CASHEW models and seismic analyses

The CASHEW model parameters K_0 and F_u (Table 7) paralleled the K_0 and P_{max} of the actual shear wall tests (Table 6). The general shapes of the backbone curves were similar, but CASHEW F_u value was 6–22% greater than P_{max} at 15–30% lower displacement (Fig. 1 and Fig. 3).

The differences between the experimental and calculated K_0 ranged from −4% for the 85-ksi walls to 14% for the 115-ksi walls, with intermediate deviations of 11% for the 145-ksi walls and 8% for the 241-ksi walls. The differences in initial stiffness estimates were not correlated with the differences in the peak capacity.

CASHEW predicted that the walls would exhibit nearly the same cumulative energy dissipation (Fig. 4) as the tested shearwalls (Fig. 2). The cumulative energy of the test shear walls was between 128,000 lb·in. and 149,000 lb·in., while the CASHEW-predicted values ranged from just under 130,000 lb·in to about 140,000 lb·in. The CASHEW-predicted energy for the 145-ksi wall was 13% lower than the tested

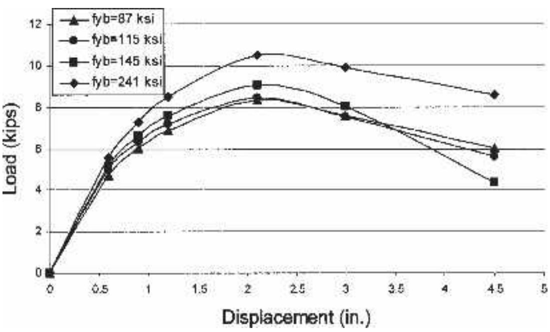

FIG. 3 Summary of CASHEW backbone curves for each sheathing nail bending-yield strength (f_{yb}).

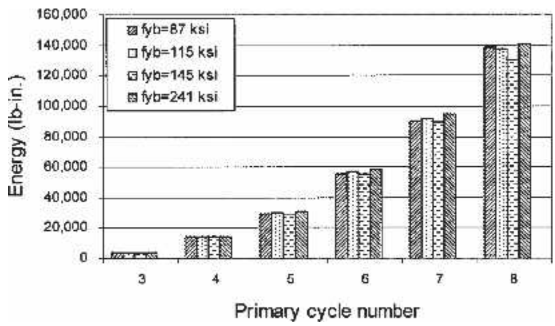

FIG. 4 Cumulative energy dissipated at the primary cycles from the shear walls evaluated with CASHEW at each f_{yb} value.

wall average. The 87-ksi walls differed by 8% and the 115-ksi and 241-ksi walls, by 1%.

The peak displacement values (one for each wall) from SASH1 for the seismic ground motions were rank-ordered and plotted as cumulative distribution functions for the life-safety (Fig. 5a) and immediate-occupancy (Fig. 5b) limit states. This type of figure can be used to evaluate the relative failure probabilities (probability of exceeding specified drift limits) for the different walls, considering different performance requirements. The FEMA drift limits (2% for life-safety and 1% for immediate-occupancy) are shown on these figures for reference. At the life-safety limit state, wall performance might be marginally improved by increasing the sheathing nail f_{yb} from 145 ksi to 241 ksi, but there appears to be no real advantage in the 85–145 ksi range. The sheathing nail

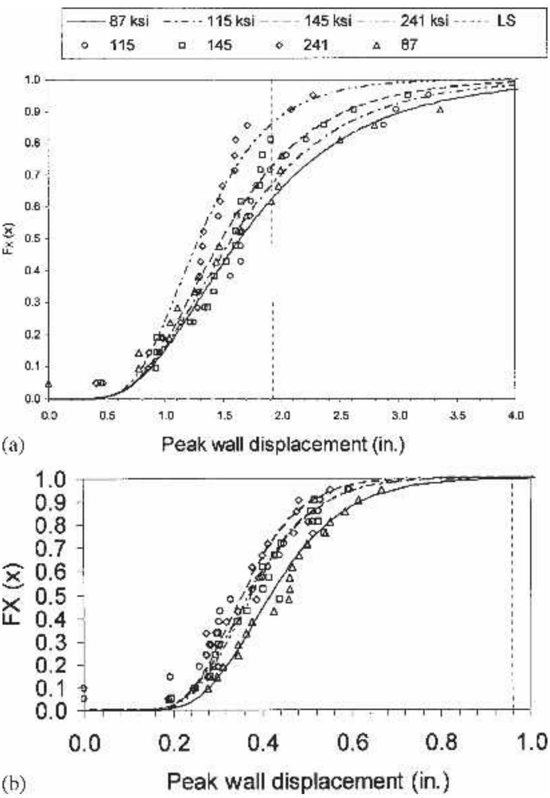

FIG. 5 Comparison of predicted peak wall displacements for (a) the life-safety limit state and (b) the immediate-occupancy limit state.

f_{yb} appeared to have no influence on the shear wall performance with respect to the immediate-occupancy limit state.

Testing and modeling synthesis

The 115-ksi sheathing nail is representative of low-carbon steel nails in this size class, and this fastener meets the building code requirements (ICC 2006). On the other hand, the 87-ksi nail has only 75% of 115-ksi nail bending-yield stress and is not in compliance with the building code. The 145-ksi and 241-ksi nails have bending-yield strengths that are 126% and 210% of the 115-ksi nail. The modulus of elasticity of the nails was not measured, but it is known that the modulus of elasticity of steel has limited variation and is not correlated with the f_{yb} value. For this reason, it is not considered to be a source of variation in the experiment and performance assessment.

The calculations of Table 2 show that connection design capacity is expected to increase in relation to nail f_{yb}. Using the 115-ksi nail as the benchmark, the 87-ksi nail should produce a connection with 9% less capacity than the 115-ksi nail. At the same time, the 145-ksi and 241-ksi nails should offer 9% and 33% capacity increases relative to the benchmark. The results of single-nail connection tests confirm the general trends from the calculations, except that the 87-ksi nails produce single-nail connections that are about equivalent to the benchmark and the 241-ksi nail produced only a 24% increase rather than the 33% increase that was expected.

As we reviewed the shear wall test data of Table 6 and used the wall test results with the 115-ksi nail as the benchmark, we saw results similar to the single-nail connection tests for the 87-ksi and 145-ksi nails. The 241-ksi nail failed to meet expectations as it produced only a 13% improvement in shear wall capacity.

Turning to the CASHEW results for the shear walls, we again used the 115-ksi nail as the benchmark for capacity change assessment. The capacity ratios for the walls are in the same ratios as the single-nail connection tests. Thus, CASHEW follows the single-nail connection performance and predicts increased F_u values of 7% and 24% for the 145-ksi and 241-ksi shear walls relative to the 115-ksi wall.

The final important comparison is between the CASHEW model and the real wall test. The model, while effectively following the single-nail connection performance, consistently produced nonconservative estimates of the real wall stiffness and capacity. We think this outcome occurs for three reasons: (1) the numerical model results rely on deterministic mean properties, (2) the single-nail connection performance is approximated by curve fitting processes, and (3) the models are not equipped with failure modes that differ from the single-fastener connections. As shown in Table 5, nail failures, especially in the wall with 145-ksi nails and 241-ksi nails, were somewhat different from the single-nail connection tests in that more fasteners failed in pull-through and tear-out modes.

As we sought a conclusion to the study based on the objectives, we assessed the results of the single-nail connection tests, shear wall tests, the CASHEW wall model tests, and the calculated seismic performance results. It is clear to us that the shear wall model is an effective tool with the exception that the model results for the 240-ksi nails are not reflective of the real wall performance.

CONCLUSIONS

The peak capacities of the shear walls were the same for walls made with 87-ksi and 115-ksi sheathing nails and for the walls made with 145-ksi and 241-ksi sheathing nails, but the two pairs were significantly different. The single-nail connection tests and the CASHEW analysis both suggested that initial stiffness of the shear wall would increase with increasing sheathing nail f_{yb}. However, the shear wall results contradicted this expectation. Initial stiffness, displacement at peak capacity, and energy dissipation were not affected by sheathing nail f_{yb}. Although the shear walls built with 115-ksi nails had the highest ductility, it was not significantly higher than in the other shear wall types.

The dominant failure mode for the sheathing nails was withdrawal; the 241-ksi nail exhibited more fatigue failure than the other nails. Wall models used to assess probable performance with respect to life-safety and immediate-occupancy limit states for a suite of seismic ground motions showed that increased sheathing nail f_{yb} did little to enhance the seismic performance of the shear walls. The two-fold increase in sheathing nail f_{yb} translated to ultimate capacity improvements on the order of 12% and no stiffness improvements in cyclically loaded shear walls. At the same time, nails that had mean f_{yb} 15% below the code minimum did not significantly detract from wall performance.

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