International Specialty Conference on Cold-Formed Steel Structures

Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures 2018

Nov 7th, 12:00 AM - Nov 8th, 12:00 AM

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Deniz Ayhan

Samuel Baer

Zhidong Zhang

Colin A. Rogers

Benjamin W. Schafer

Recommended Citation

Ayhan, Deniz; Baer, Samuel; Zhang, Zhidong; Rogers, Colin A.; and Schafer, Benjamin W., "Cold-Formed Steel Framed Shear Wall Database" (2018). *International Specialty Conference on Cold-Formed Steel Structures*. 3.
https://scholarsmine.mst.edu/isccss/24iccfss/session9/3

Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, U.S.A., November 7 & 8, 2018

Cold-Formed Steel Framed Shear Wall Database

Deniz Ayhan[1], Samuel Baer[2], Zhidong Zhang[3],
Colin A. Rogers[4], Benjamin W. Schafer[5]

Abstract

The objective of this paper is to provide an introduction to a recently compiled database of cold-formed steel framed shear wall tests and demonstrate the application of this database for improving the understanding and modeling of cold-formed steel framed shear walls. Over the last 20 years a substantial number of cold-formed steel framed shear walls have been tested under monotonic and cyclic conditions. These tests provide the support for the cold-formed steel framed shear wall provisions provided in the North American Standard for Cold-Formed Steel Structural Framing (AISI S240-15), the North American Standard for Seismic Design of Cold-Formed Steel Structural Systems (AISI S400-15), and the U.S. Seismic Evaluation and Retrofit of Existing Buildings standard (ASCE41-17). The initial version of the database was assembled during the development of ASCE41-17. The database has recently been expanded to include additional tests, additional complete cyclic information from tests, additional fields regarding limit states and code predictions, and placed in a standardized format. The database consists of a central Excel spreadsheet, ordered plain text files for each individual test, and custom Matlab code for reading, processing, and plotting any desired subset of the database. As a new application of the assembled database the expected strength of cold-formed steel framed shear walls is explored. The information in the database is summarized herein, along with commentary on current code provisions, and areas of potential improvement and need.

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[1] Visiting Scholar, Johns Hopkins University, Baltimore, MD, USA
[2] Graduate Research Assistant, Johns Hopkins University, Baltimore, MD, USA
[3] Graduate Research Assistant, Johns Hopkins University, Baltimore, MD, USA
[4] Professor, McGill University, Montreal, QC, Canada
[5] Professor, Johns Hopkins University, Baltimore, MD, USA

Introduction

Buildings framed from cold-formed steel rely on a variety of systems to develop lateral resistance. Summaries of the overall behavior, design, and performance of cold-formed steel lateral force resisting systems area available (Madsen et al. 2016). Under load, the response of the lateral force resisting system can be complex, particularly under seismic loading. Depending on the system, significant nonlinearity may be induced at connections, in the framing steel, and/or in any sheathing materials. Prediction, even of fundamentals such as the lateral capacity, can be challenging. As a result, experimental testing has played a prominent role in understanding the behavior and providing guidance for the design of cold-formed steel framed lateral force resisting systems. Cold-formed steel specifications, such as the North American Standard for Cold-Formed Steel Structural Framing (AISI S240-15), the North American Standard for Seismic Design of Cold-Formed Steel Structural Systems (AISI S400-15), and the Seismic Evaluation and Retrofit of Existing Buildings standard (ASCE41-17) rely directly on the available test data. As a result, a comprehensive database of tested cold-formed steel framed shear walls is expected to provide a necessary means for improving current design of cold-formed steel framed systems.

Database Summary

The assembled database of cold-formed steel framed shear walls currently consists of 617 individual shear wall tests. A serious attempt has been made to include all cold-formed steel framed shear wall testing that underpins AISI S240-15, and AISI S400-15. The initial version of this database supported recent revision in ASCE41-17 for cold-formed steel framing (Ayhan et al. 2016). The shear wall tests are currently drawn from 25 different primary sources: Al-Kharat and Rogers (2005), Al-Kharat and Rogers (2006), Balh and Rogers (2010), Blais (2006), Boudreault (2005), Branston (2004), Chen (2004), Comeau (2008), DaBreo (2012), El-Saloussy (2010), Elhajj (2005), Hikita (2006), Kochkine and Hill (2006), Liu et al. (2012), Lu (2015), Morello (2009), Morgan et al. (2002), Nguyen et al. (1996), Ong-Tone (2009), Rokas (2006), Serrette et al. (1997), Shamim (2012), Velchev (2008), Yu and Chen (2009), and Yu et al. (2007)). The database itself consists of an Excel spreadsheet, text data files for every test, the source literature, and custom Matlab scripts that read the spreadsheet and the test data files and may be used for deeper manipulation of the data. The fields in the primary database are summarized in Table 1. The fields attempt to capture all salient features of the tested walls. In general, English customary units have been used in the database. Every variable listed in Table 1 may be manipulated in Excel, or more powerfully read into Matlab and utilized through scripts in Matlab.

Table 1 Database fields for the CFS shear wall database

category	units	variable	category	units	variable	category	units	variable
basic_identification	na	id	chord_stud_details	na	chord_config	bridging_details	na	bridging_loc
	na	source			chord_fastener_qty		in.	bridging_web
	na	test_no		na	chord_fastener_dia		in.	bridging_flange
	na	loading_detail			chord_fastener_pitch		in.	bridging_t
wall_overall	na	loading			chord_fastener_length	holddown	kip	holddown_id
	ft	width		in.	chord_fast_spacing		na	holddown_no
	ft	height		in.	chord_web		in.	holddown_offset
	na	h_on_w		in.	chord_flange	opening_details	na	opening_id
	in.	thickness		in.	chord_lip		ft	opening_dim
	na	Designation1		in.	chord_t	ledger_details	na	ledger_id
	na	Designation2		ksi	chord_nom_Fy			
	na	sides		ksi	chord_act_Fu	limit_stat	na	limit_primary
strap_bracing_details	na	strap_detail		ksi	chord_actual_Fy		na	limit_listed
	in.	strap_width	field_stud_details	in.	field_spacing		na	limit_failure_notes
	in.	strap_thickness		in.	field_web	AISI S400-15	na	S400_applicable
	ksi	strap_grade		in.	field_flange		kN/m	S400_vn_CAN
	ksi	strap_actual_Fu		in.	field_lip		lb/ft	S400_vn_USA
	ksi	strap_actual_Fy		in.	field_t		na	s400_notes
	na	strap_Ry		ksi	field_nom_Fy	data_files	na	data_units
sheathing_details	na	she_details		ksi	field_actual_Fu		na	data_note
	na	she_sides		ksi	field_actual_Fy		na	data_dir
	in.	she_thickness	track_details	in.	track_web		na	data_main
	ksi	she_strength		in.	track_flange		na	data_raw_txt
	ksi	she_Fu		in.	track_t		na	data_raw_xls
	ksi	she_Fy_actual		ksi	track_nom_Fy		na	data_raw_image
	na	she_fastener_diam		ksi	track_actual_Fu	processed_data_files	na	proc_dxf
	na	she_fastener_pitch		ksi	track_actual_Fy		na	proc_cyclic
	in.	she_fastener_len	fastener_stud_track	na	fastener_stud_track_no		na	proc_mono
	in.	she_spacing_perimeter			fastener_stud_track_len		na	proc_backb
	in.	she_spacing_field	gusset_plate_details	in.	gusset_id		na	proc_backb_ave
				in.	gusset_width			
				in	gusset_t			
				ksi	gusset_nom_Fy			
				ksi	gusset_actual_Fu			
				ksi	gusset_actual_Fy			

A key feature of the developed database is that full test response is available for 461 of the tests, thanks to the generosity of the original researchers. An additional 119 tests have been scanned and digitized from the source literature and the final 37 are currently being processed. In the database: 300 of the tests employ a cyclic loading protocol; further 260 tests utilize wood structural panels, 179 steel sheet sheathing, 117 strap bracing, 40 gypsum sheathing, and 21 other configurations. The force-deformation response of the four largest categories of tested shear walls are provided for the entire ensemble in Figure 1. The figure provides some sense of the available data and the overall hysteretic shape of the different cold-formed steel framed shear wall types. Recent testing by Rogers (Santos and Rogers 2017, Briere and Rogers 2017, Rizk and Rogers 2017) that has specifically been exploring higher capacity steel sheet sheathed shear walls are not captured in the current database, but it is worth noting these walls have provided in the lab up to 10,000 lbf/ft capacity – the highest of any cold-formed steel framed shear walls tested to date. Inclusion of this data is the next to be added to the database.

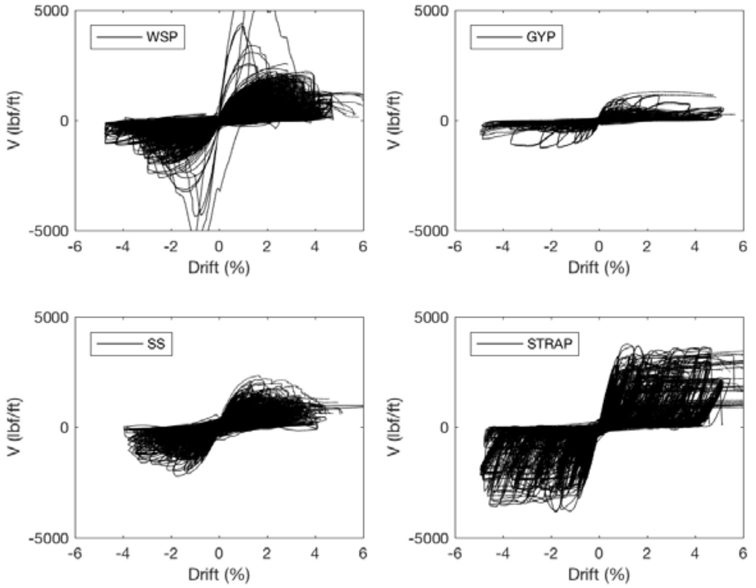

Figure 1 Normalized drift vs. strength for all data in shear wall database

Database Application: Expected Strength

Seismic design has long included the concept of system overstrength, as embodied by the Ω_o factor in the U.S. in ASCE 7, or by R_o in Canada in the NBCC. These factors account for the fact that lateral force resisting systems in actual buildings are stronger than the strengths considered in engineering design. If one assumes a capacity-based design philosophy this overstrength is critically important, as only specific parts of the building are designated to dissipate the seismic energy while other portions are intended to remain elastic. These elastic portions of the lateral force resisting system must be designed at overstrength levels so that the energy dissipating elements can be activated.

Research has shown that for cold-formed steel framed buildings the system overstrength can be quite large (Peterman et al. 2016). Several important sources for building system overstrength come from outside the designated shear walls, e.g., sheathed gravity walls, non-structural partitions, out-of-plane wall response, and in-plane coupling of walls. As a result AISI S400-15 introduced the concept of a sub-system overstrength specific to the portion of the lateral force resisting system explicitly designed by the engineer to resist the lateral demand, e.g., a wood structural panel shear wall. The overstrength for the shear wall is termed the expected strength of the shear wall, and is designated by the multiplier Ω_E. This sub-system overstrength provides the force levels to protect the shear wall in isolation. Consistent with a capacity-based philosophy the collectors, chords, and hold-downs for the shear wall are designed for the expected strength ($\Omega_E v_n$, where v_n is the nominal shear wall strength per unit width), but this need not exceed the required demands from the building at full system overstrength (Ω_o) levels.

In concept $\Omega_E < \Omega_o$ and as long as the walls are not over-sized (v_n much larger than required) the expected strength (Ω_E) levels provide capacity protection and a more efficient design than Ω_o levels. When AISI S400-15 was developed there was insufficient time to evaluate the expected strength of all shear walls and an upperbound for Ω_E was employed: $\Omega_E = \max(\phi\Omega_o, 2 - \phi)$ (see AISI S400-15 commentary). For a wood structural panel shear wall $\phi = 0.6$ and $\Omega_o = 3$, so the upperbound estimate of Ω_E is 1.8. In practice, to benefit from the expected strength concept Ω_E must be lower than this upperbound.

Conceptually, the expected strength should be established from knowledge of the reliability and statistical variation of the nominal strength prediction for the seismic force resisting system. Assuming the nominal shear wall strength is v_n, the actual (tested) shear wall strength is v_a, and the mean of any walls tested consistent with v_n is μ_{va}, then the first estimate of the expected strength is:

$$\Omega_{E1} = \mu_{va}/v_n \tag{1}$$

For wood structural panel and steel sheet shear walls AISI S400-15 provides tabled capacities – thus the phrase "consistent with v_n" implies only those tests that are consistent with a particular table entry. It is worth noting that Ω_{E1} provides only the mean shift, i.e., the bias in the nominal prediction for strength. In some contexts a higher level of reliability may be desired for capacity protection, for example AISC 342 which is currently under development (and intended to be used with the seismic performance-based design standard ASCE41-17) employs the mean plus one standard deviation, thus giving a second estimate, Ω_{E2}:

$$\Omega_{E2} = (\mu_{va}+\sigma_{va})/v_n \tag{2}$$

Where σ_{va} is the standard deviation of the strength of walls tested consistent with v_n. The shear wall database provides the necessary tested strength predictions.

For the purposes of expected strength calculation it is important to make a distinction between the U.S. and Canada. Nominal seismic force resisting system shear strengths provided for Canadian design adopt an equivalent energy elastic-plastic model. While the U.S. (generally) employs the maximum value in the cyclic backbone curves from testing. Thus, the nominal tabled capacities for Canada are different than the U.S., even when derived from the same actual test data. As the nominal capacities are in the denominator of Eq.'s (1) and (2) the result is that even for the same data the expected strength predictions will differ.

Expected Strength of Wood Structural Panel Shear Walls

In the U.S. the nominal strength of wood structural panel shear walls is provided in AISI S400-15 Table E1.3-1. The strength values in the table were selected by the specification committee based on data and methods available at the time of adoption. In some cases methods have evolved, e.g. use of the SPD vs. CUREE cyclic testing protocol, or use of the 2nd stable cycle vs. the first cycle for establishing peak capacity. In other cases additional testing has been conducted since adoption, providing additional information on the strength. In addition, in some cases the committee has grouped data together, e.g. multiple stud thicknesses, and taken data from the lower thickness only leaving a conservative bias (overstrength) when the higher thickness is employed. Here we evaluate the tabled nominal strength against the peak of the tested cyclic backbone response from all available testing consistent with the conditions for an entry in Table E1.3-1. The results are provided in Table 2(a)-(c) and Figure 2 and Figure 3.

Table 2. Wood structural panel shear walls strength and expected strength statistics

(a) nominal shear strength, lbf/ft, for wood structural panel shear walls (AISI S400-15)

Assembly	Max Aspect Ratio	Perim. screw spacing (in.)				Stud & Track (mils)	Screw
		6	4	3	2		
15/32 in. Structural 1 (4-ply)	2:1	780	990	-	-	33 or 43	8
	2:1	890	1330	1775	2190	43 or 54	8
						68	10
7/16 in. OSB	2:1	700	915	-	-	33	8
	2:1	825	1235	1545	2060	43 or 54	8
	2:1	940	1410	1760	2350	54	8
	2:1	1230	1850	2310	3080	68	10

(b) expected strength, estimated as mean test strength/nominal strength

Assembly	Max Aspect Ratio	Perim. screw spacing (in.)				Stud & Track (mils)	Screw
		6	4	3	2		
15/32 in. Structural 1 (4-ply)	2:1	1.44	1.70	-	-	33 or 43	8
	2:1	1.23	1.26	1.30	1.22	43 or 54	8
						68	10
7/16 in. OSB	2:1	1.34	1.42	-	-	33	8
	2:1	1.06	0.96	1.06	1.22	43 or 54	8
	2:1	1.23	-	0.91	1.10	54	8
	2:1	-	-	-	1.06	68	10

(c) supplemental statistics (std. dev. of mean test strength/nominal strength, count)

Assembly	Max Aspect Ratio	Perim. screw spacing (in.)				Stud & Track (mils)	Screw
		6	4	3	2		
15/32 in. Structural 1 (4-ply)	2:1	(0.12,3)	(0.02,3)	-	-	33 or 43	8
	2:1	(0.10,3)	(0.02,3)	(0.04,9)	(0.05,2)	43 or 54	8
						68	10
7/16 in. OSB	2:1	(0.11,2)	(0.07,2)	-	-	33	8
	2:1	(0.23,8)	(0.01,3)	(0.06,8)	(0.08,4)	43 or 54	8
	2:1	(0.15,2)	-	(0.07,3)	(0.01,2)	54	8
	2:1	-	-	-	(0.06,2)	68	10

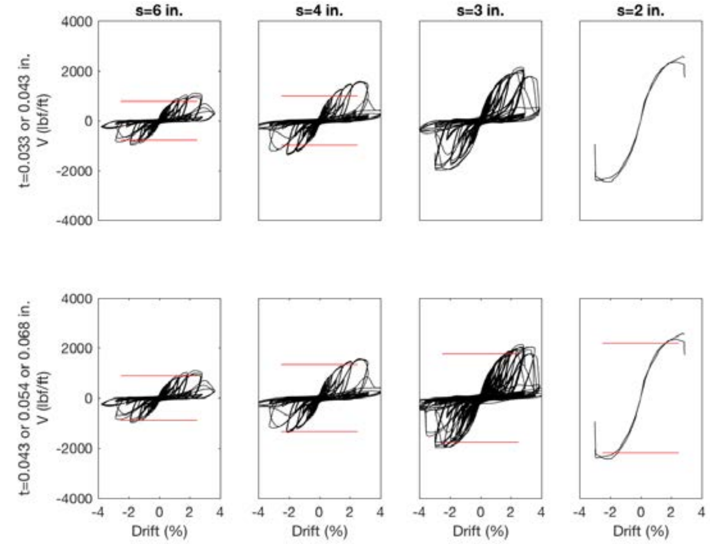

Figure 2 For plywood sheathed shear walls, comparison of tested shear wall response with code prediction (red line)

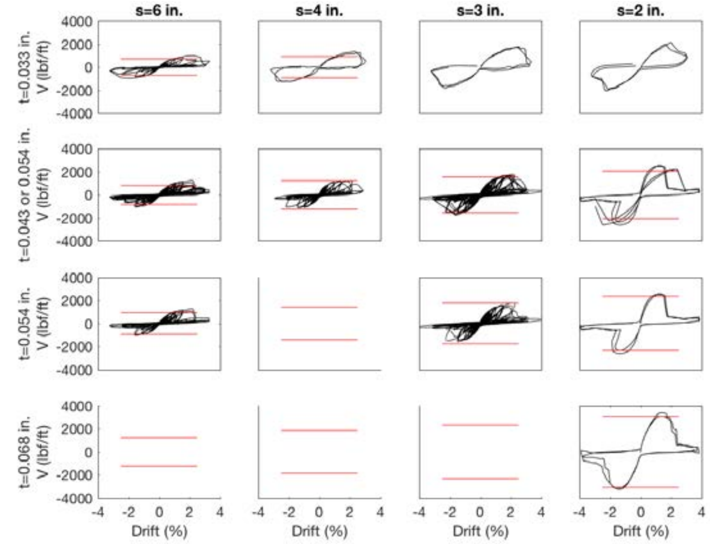

Figure 3 For OSB sheathed shear walls, comparison of tested shear wall response with code prediction (red line)

The expected strength measures and statistics for wood structural panel shear walls are provided in Table 2(b) and (c). Across the 23 plywood sheathed shear walls that meet the criteria of Table E1.3-1 Ω_{E1}=1.35 and Ω_{E2}=1.35+0.16. Across the 36 OSB sheathed shear walls that meet the criteria of Table E1.3-1 Ω_{E1}=1.10 and Ω_{E2}=1.10+0.17. Note, only cyclically tested walls with aspect ratios greater than or equal to two are considered. For individual configurations these values vary as provided in Table 1(b) and (c). The larger expected strength for the plywood specimens does not reflect a behavioral difference between the different types of wood structural panels, but rather evolving philosophies in testing and in the committee's adoption of strength values. The plywood specimens were originally tested to the SPD protocol and utilized the second cycle degraded cyclic backbone for establishing the strength. Further, more stud thicknesses were grouped together in plywood sheathed specimens. The OSB sheathed specimens were tested to the CUREE protocol, and in the United States used the undegraded cyclic backbone for establishing strength.

Expected Strength of Steel Sheet Shear Walls

In the U.S. the nominal strength of steel sheet sheathed shear walls is provided in AISI S400-15 Table E2.3-1. Here we evaluate the tabled nominal strength against the peak of the tested cyclic backbone response from all available testing consistent with the conditions for an entry in the table. Note, only cyclic tests of walls with aspect ratios less than or equal to two are included. The results are provided in Table 3(a)-(c). Across the 44 cyclically tested steel sheet sheathed shear walls that meet the criteria of AISI S400-15 Table E2.3-1 Ω_{E1}=1.12 and Ω_{E2}=1.12+0.17. For individual configurations these values vary as provided in Table 3(b) and (c). However, for the single entry with the most specimens (0.033 in. sheet, 2 in. perimeter fastener spacing, 43 mil minimum stud and track, fully blocked studs, 8 tested specimens) the results are similar to the larger group: Ω_{E1}=1.13 and Ω_{E2}=1.13+0.17.

Table 3. Steel sheet shear walls strength and expected strength statistics

(a) nominal shear strength, lbf/ft, for steel sheet shear walls (AISI S400-15)

Steel Sheet	**Max Aspect Ratio**	**Perim. screw spacing (in.)**				**Stud Blocking**	**Stud & Track (mils)**	**Screw**
		6	**4**	**3**	**2**			
0.018 in.	2:1	390	-	-	-	No	33 (min)	8
0.027 in.	2:1	647	710	778	845	No	33 (min)	8
	2:1	-	1000	1085	1170	No	43 (min)	8
0.030 in.	2:1	910	1015	1040	1070	No	43 (min)	8
	2:1	-	-	-	1355	Yes	43 (min)	10
0.033 in.	2:1	1055	1170	1235	1305	No	43 (min)	8
	2:1	-	-	-	1505	Yes	43 (min)	10
	2:1	-	-	-	1870	No	54 (min)	8
	2:1	-	-	-	2085	Yes	54 (min)	10

(b) expected strength, estimated as mean test strength/nominal strength

Steel Sheet	**Max Aspect Ratio**	**Perim. screw spacing (in.)**				**Stud Blocking**	**Stud & Track (mils)**	**Screw**
		6	**4**	**3**	**2**			
0.018 in.	2:1	1.18	-	-	-	No	33 (min)	8
0.027 in.	2:1	1.05	1.03	-	1.17	No	33 (min)	8
	2:1	-	-	-	1.28	No	43 (min)	8
0.030 in.	2:1	1.04	-	-	-	No	43 (min)	8
	2:1	-	-	-	1.03	Yes	43 (min)	10
0.033 in.	2:1	1.08	1.06	-	1.28	No	43 (min)	8
	2:1	-	-	-	1.13	Yes	43 (min)	10
	2:1	-	-	-	1.06	No	54 (min)	8
	2:1	-	-	-	1.01	Yes	54 (min)	10

(c) supplemental statistics (std. dev. of mean test strength/nominal strength, count)

Steel Sheet	**Max Aspect Ratio**	**Perim. screw spacing (in.)**				**Stud Blocking**	**Stud & Track (mils)**	**Screw**
		6	**4**	**3**	**2**			
0.018 in.	2:1	(0.11,6)	-	-	-	No	33 (min)	8
0.027 in.	2:1	(0.01,2)	(0.04,2)	-	(0.34,5)	No	33 (min)	8
	2:1	-	-	-	(N/A,1)	No	43 (min)	8
0.030 in.	2:1	(0.02,2)	(N/A,1)	-	-	No	43 (min)	8
	2:1	-	-	-	(0.01,2)	Yes	43 (min)	10
0.033 in.	2:1	(0.01,2)	(0.01,2)	-	(0.27,4)	No	43 (min)	8
	2:1	-	-	-	(0.17,8)	Yes	43 (min)	10
	2:1	-	-	-	(0.01,2)	No	54 (min)	8
	2:1	-	-	-	(0.07,2)	Yes	54 (min)	10

Expected Strength of Strap Braced Shear Walls

The nominal strength of strap braced shear walls is provided in AISI S400-15 Equation E3.3.1-1, converting to strength per unit width and making substitutions the nominal strength per unit wall width, v_n, may be expressed as:

$$v_n=A_gF_{yn}/\sqrt{h^2+w^2}$$

where A_g is the gross area of the strap, F_{yn} is the nominal yield stress of the strap, w is the width of the wall, h is the height of the wall, and AISI S400-15 provides additional provisions to insure strap yielding is the governing limit state. The expected strength is defined as R_y times the nominal strength in AISI S400-15 and values for R_y are provided in Table A3.2-1 of AISI S400-15. R_y is the ratio of the mean actual material yield stress to the nominal yield stress.

From the database we find 38 cyclic tests on strap-braced walls where the governing limit state was strap yielding, and the aspect ratio of the tests is less than two. In 34 of the 38 tests the strap yield stress was measured, so we may compare the measured R_y to that assumed in AISI S400-15, as provided in Figure 4. Only two nominal grades of strap have been employed: F_{yn} = 33 or 50 ksi – and for many of the specimens the same strap materials was used so a single point in the figure may represens multiple test specimens (a total of 11 unique strap materials has been used in the available testing). The available data indicates that the mean yield stress is reasonably well predicted by the R_y in AISI S400-15.

For the same 38 cyclic tests, instead of exploring the expected strap material yield stress (R_y), we may instead consider the tested wall expected strength (Ω_E). This strength may be greater than the strap strength due to increased capacity from strain hardening in the strap material or additional strength contributions from frame action in the wall – particularly for those walls with substantial gusset plates. The result for the tests are provided in Figure 5. For the 26 cyclically tested strap braced shear walls with a nominal strap F_{yn} of 33 ksi, R_y is 1.5 from AISI S400-15 Table A3.2-1 while Ω_{E1}=1.51 and Ω_{E2}=1.51+0.24. For the 12 cyclically tested strap braced shear walls with a nominal strap F_{yn} of 50 ksi, R_y is 1.1 from AISI S400-15 Table A3.2-1 while Ω_{E1}=1.39 and Ω_{E2}=1.39+0.29.

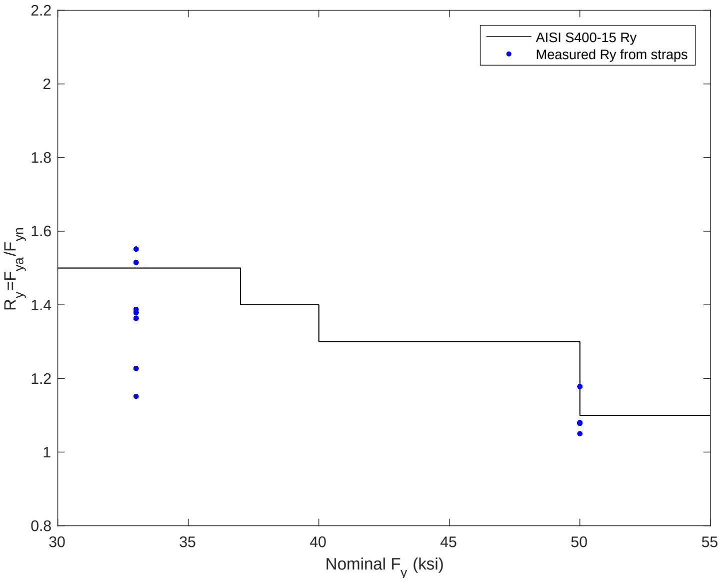

Figure 4 Ratio of mean to nominal yield stress for steel strap employed in available strap-braced shear wall testing

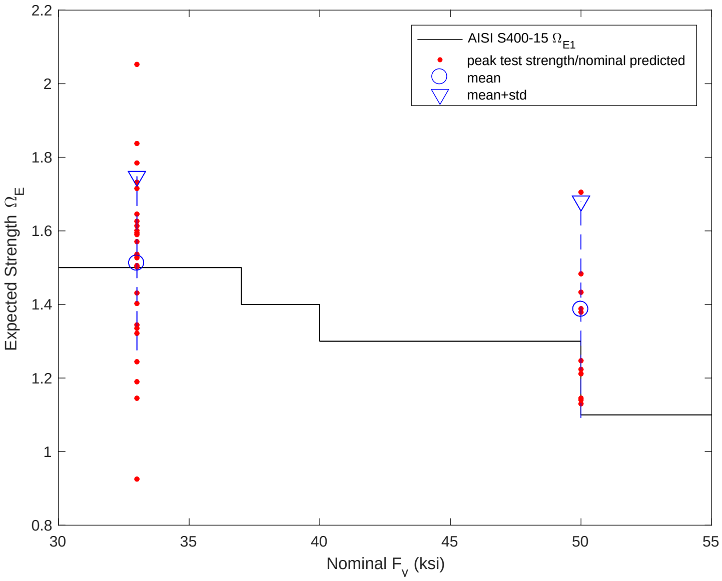

Figure 5 Ratio of tested to nominal strength for strap-braced shear walls

Discussion

Overall the developed shear wall database has significant potential for improving design: revision and improvement of m-factors and nonlinear modeling parameters for ASCE 41; revision of fragilities for FEMA P-58; revision of shear wall reliabilities in AISI S240 and AISI S400; revision of deflection predictions; calibration and validation of mechanics-based strength and stiffness prediction models; calibration and validation of advanced nonlinear response models for building-level seismic models; and more. The application explored herein is seismic expected strength.

Expected strength of a shear wall is an important concept in seismic design. The application of the cold-formed steel framed shear wall database indicates that improvements can be made from currently assumed values. It is worth noting that there are other considerations that contribute to the expected strength beyond those previously discussed (testing protocol, definition of nominal strength from test response, variation in materials and assembly, etc.). Most importantly the impact of fireproofing and finish systems. Tests on strap-braced walls with additional gypsum board fire protection provided on average an increase in 1.2 times the strength of the unprotected walls for a single gypsum board layer and 1.3 times the strength of the unprotected walls for a double gypsum board layer (Lu 2015). The impact of finish or protection systems depends on the influence of the attachment methods on the shear wall performance and the relatives stiffness and strength of the finish or protection system compared with the underlying seismic force resisting system. The results of the analysis herein will be shared with the American Iron and Steel Institute - Committee on Framing Standards: Lateral Design Subcommittee to develop improved expected strength provisions.

Conclusions

Lateral force resisting systems are an integral portion of cold-formed steel framed building solutions. Due to the complexity in the lateral force-deformation response a significant effort has been expended to test various cold-formed steel framed shear walls. A database of 617 tested shear walls including walls sheathed with wood structural panel, steel sheet, and gypsum board; as well as strap braced has been assembled. A key feature of the developed database is that full test response is available for 461 of the tests, thanks to the generosity of the original researchers. An example of how the database can be used is provided by estimating the seismic expected strength (i.e., overstrength) of wood structural panel, steel sheet, and strap braced cold-formed steel framed shear walls. Compared with AISI S400-15 the analysis indicates that more efficient overstrength values may be adopted for wood structural panel and steel sheet sheathed shear walls, but modest increases in overstrength may be appropriate for strap braced shear walls, particularly when the nominal strap yield is 50 ksi (345 MPa). The database provides important and useful information for seismic performance-based design efforts and any effort to improve lateral force resisting systems in cold-formed steel framing.

Acknowledgments

The authors wish to extend their thanks to high school student researcher Alex Nishiura who assisted with digitizing some of the data used in this work. This material is partially based upon work supported by the U.S. National Science Foundation under Grant No. 1663348. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. National Science Foundation.

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