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Overstrength in seismic design of cold-formed steel framed shear walls

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Abstract

The objective of this paper is to re-assess seismic overstrength for cold-formed steel-framed shear walls in light of a recently compiled database of cold-formed steel shear wall tests and consistent with current practice established in ASCE 7 and AISI S400. AISI S400 has established a capacity-based design philosophy whereby elements that are designed to remain elastic, and/or protect the energy dissipating portions of the seismic force resisting system, are designed for an elevated strength using the overstrength multiplier. In AISI S400-15 this multiplier was established using engineering judgment on the expected maximum bounds. We recently compiled a database of over 700 monotonic and cyclic cold-formed steel framed shear wall tests, spanning walls with wood structural panel sheathing, steel sheet sheathing, and strap bracing. These tests form the primary basis for the re-evaluation of the overstrength multiplier known as the expected strength factor. Care must be taken to insure that the selected specimens from the database are consistent with the detailing requirements of AISI S400. For those tests that are valid, direct comparison of the strength in the shear wall tests versus that specified in AISI S400 are used to examine the ratio of the mean tested strength over the nominal strength from AISI S400. Finish systems on the wall can greatly influence this strength ratio and the existing data is utilized to justify a simple additive model for the impact of finish systems. Finally, an expected strength factor for CFS frames, including the effect of finished systems, is formalized and recommended for use in seismic design of CFS framed shear walls.

1. Introduction

In the U.S. cold-formed steel (CFS) seismic force resisting systems are designed and detailed per AISI S400 [1]. The basic attributes of these systems are detailed in [2] and a recent design guide provides practical calculations [3]. A key feature of AISI S400 is that for each seismic force resisting system the energy dissipating mechanism is identified – and then protected. The protection is through capacity-based design principles whereby components in the load path of the energy dissipating mechanism are designed for the expected (mean) strength of the energy dissipating mechanism.

For example, in a strap-braced CFS wall the chord studs of the shear wall are designed for the expected strength of the straps since the straps are the designated energy dissipating mechanism. For sheathed shear walls the expected strength was not fully characterized in [1] and conservative approximations related to the overall system overstrength, Ω_o, from ASCE 7 [4] were instead employed. This paper provides an assessment of available experimental data to determine CFS seismic force resisting system expected strength.

2. Expected Strength in AISI S400

Consider a wall of width, w, and height, h, that has a demand shear, V_r, that is required to be carried based on ASCE 7 [4] demands and a structural analysis. The design strength of the wall, ϕV_n, where resistance factor ϕ and nominal strength V_n, must be greater than or equal to the required strength, i.e.:

$$\phi V_n \geq V_r \tag{1}$$

Note, this calculation may be performed on a per unit length basis, i.e. where $v_n = V_n/w$ and $v_r = V_r/w$. In traditional

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design statics of the wall would require that the chord stud would need to be designed for the axial force:

$$P_r^* = V_r \frac{h}{w} \quad (2)$$

However, to protect the energy dissipating element in the seismic force resisting system we instead design the chord stud based on the expected strength of the shear wall:

$$P_r = \Omega_E V_n \frac{h}{w} \leq \Omega_o P_r^* \quad (3)$$

where P_r is the required demand on the chord stud, Ω_E is the expected strength factor, and Ω_o is the system overstrength factor from ASCE 7 [4]. Note, if a wall is over-designed and $V_n >> V_r$ then there is no need to capacity protect beyond the level of system overstrength as established by Ω_o. Determination of Ω_E is the subject of this paper.

3. Shear Wall Database

The primary method for evaluation of shear wall expected strength provided here is the application of a recently compiled database of cold-formed steel shear wall tests. A series of conference papers [5-7] describe the shear wall database in detail. Over 700 tests from 29 primary sources [8-36] are included in the database.

4. CFS Framed Shear Walls without Finish

To determine the expected strength we first assessed the mean bias (i.e., mean overstrength) of the tested shear wall strength vs. the nominal strength as calculated per AISI S400-15/S1-16 [1] for walls without any finish. Only tests that met the detailing requirements of AISI S400 were included in the comparison. Only cyclic test results were included in the comparison. More detailed breakdowns and discussion are provided in [7], here we provide the simple ensemble statistics, first for the shear walls, in Table 1.

Table 1 Ensemble peak test to nominal strength comparisons for cold-formed steel framed sheathed shear walls without finish

	V_{test}/V_n		
Sheathing	mean	COV	n
Wood Structural Panel (WSP)	1.14	0.15	62
Steel Sheet (SS)	1.16	0.20	60

The mean bias in the test-to-nominal strength ratio for strap-braced walls must be treated with slightly more care as one must also consider the known expected strength of the strap material that is yielding, i.e. $R_y F_y$ in AISI S400. The summary statistics are provided in Table 2.

Table 2 Ensemble peak test to nominal strength comparisons for strap-braced cold-formed steel framed shear walls without finish

	V_{test}/V_n		
	mean	COV	n
Strap braced wall (F_{yn}=33ksi, 228MPa)	1.51	0.16	26
Strap braced wall (F_{yn}=50ksi, 345MPa)	1.38	0.21	14
	F_{yn}/F_{ya}		
	mean	COV	n
Strap only (F_{yn}=33ksi, 228MPa) R_y=1.5	1.39	0.08	22
Strap only (F_{yn}=50ksi, 345MPa) R_y=1.1	1.11	0.05	13
	$V_{test}/(R_y V_n)$		
	mean	COV	n
Strap braced wall (F_{yn}=33ksi, 228MPa)	1.01	0.23	26
Strap braced wall (F_{yn}=50ksi, 345MPa)	1.25	0.22	14

Strap yielding is the fundamental mechanism in the response. From Table 2 we observe that the bias in strap yielding is well captured by R_y, but there is still substantial overstrength in the walls tested with F_{yn}=50ksi (345MPa) straps. These walls were all tested by Rogers and generally included large gusset plates at the corners resulting in fully engaging frame action of the walls, it is hypothesized that the gusset plates and resulting frame action are the primary source of the additional capacity in this system.

5. Impact of Finish Systems

Finish on a shear wall (gypsum board, EIFS, etc.) can substantially increase the peak strength. In the U.S., AISI S400 does not account for this increased capacity in nominal strength. However, the expected strength, which is utilized to ensure capacity protection of the energy dissipating mechanism should account for this probable overstrength. Shear wall test data on cold-formed steel framed shear walls with finish exists, but is relatively limited. Table 3 provides the ensemble statistics on tested shear walls in the Shear Wall Database that include finish.

Table 3 Ensemble statistics for cold-formed steel framed sheathed shear walls with finish (monotonic and cyclic testing)

	V_{test}/V_n		
Sheathing	mean	COV	n
Oriented Strand Board (OSB) + Gypsum Board	1.58	0.11	8
Strap braced wall[1] + 1 layer Gypsum Board	1.28	0.02	4
Strap braced wall[1] + 2 layer Gypsum Board	1.49	0.11	12
	$V_{test}/(R_y V_n)$		
Strap braced wall[1] + 1 layer Gypsum Board	1.16	0.02	4
Strap braced wall[1] + 2 layer Gypsum Board	1.35	0.12	12

1. strap F_{yn}=50ksi (345MPa), R_y=1.1

The provided strength statistics show that finish can provide a substantial contribution to the observed strength in a shear wall or strap-braced wall test. However, the provided strength statistics present a potentially misleading picture of the impact of gypsum board finish. In all tests in the Shear wall Database the gypsum board is directly attached to the perimeter framing. However, direct testing of gypsum board sheathed walls has shown that the details of how the perimeter of the gypsum board is attached to the frame have a strong impact on the strength delivered. Thus, the use of a simple expected strength constant (e.g., 1.5) for finish systems may substantially overcount the influence and lead to inefficient design.

A common and simplistic strategy for predicting the strength of systems with multiple elements in shear is to assume the strength is additive. Such an approach is often found to be potentially unconservative for nominal strength design and thus modifications are made (e.g. AISI S400 uses either two times the weaker material or one times the stronger material as a lower bound strength prediction for dis-similar sheathing on shear walls). However, for expected strength a simple additive approach may provide a reasonable upper bound approximation. To assess such a method the strength of the finish system in isolation is needed; thus, this aspect is examined next.

5.1 Strength of gypsum board sheathed walls in shear

The AISI S400 tabled values for the nominal strength of gypsum sheathed shear walls are provided in Table E6.3-1 and excerpted here as Table 4. The tabled values require that the gypsum board is attached to the stud and track on its perimeter, or fully blocked. For unblocked gypsum board 0.35 times the nominal strength is recommended.

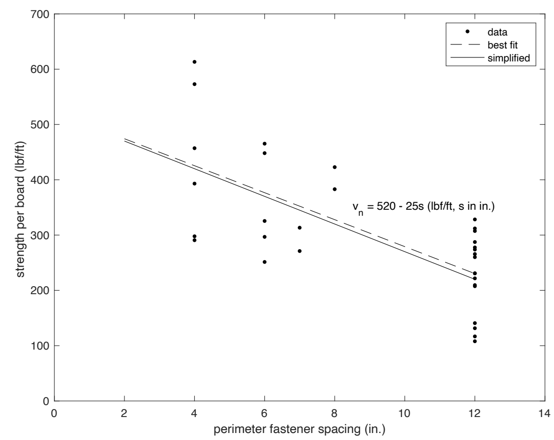
Table 4 Nominal shear strength (v_n) per unit length for gypsum or fiberboard one-sided sheathed shear walls (lbf/ft)

Assembly Description	Maximum Aspect Ratio (h:w)	Fastener Spacing at Panel Edges/Field (in.)							Designation Thickness of Stud and Track (mils)	Required Sheathing Screw Size
		7/7	4/4	4/12	8/12	4/6	3/6	2/6		
½" gypsum board; studs max. 24" o.c.	2:1	290	425	295	230	-	-	-	33	6
½" fiberboard; studs max. 24" o.c.	1:1	-	-	-	-	425	615	670	33	8

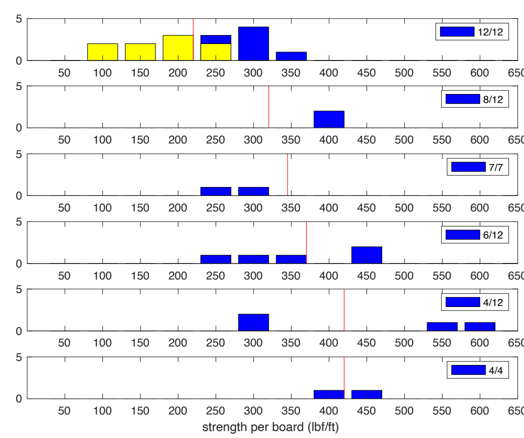
Key seismic details: all sheathing edges are attached to structural members or panel blocking. If sheathing long direction is perpendicular to the studs the horizontal strap blocking must include full depth in-line blocking of the last two studs at each end of the strap. Unblocked assemblies are permitted at 0.35 times the tabled values.

The Table 4 values were based on limited testing from [32] and [33] and the Shear Wall Database includes additional newer tests from [18], [22] and [31]. Strength from the newer tests is typically higher than the earlier values for nominally similar tests, the mean peak test strength to nominal strength for gypsum sheathed shear walls is 1.35, so the direct use of Table 4 to estimate the added strength for the purposes of predicting the expected strength may not provide a reliable response for expected strength prediction. In addition, Table 4 does not include the common case of gypsum attached at 12/12 (12 in. (305mm) o.c. on the perimeter and 12 in. (305mm) o.c. in the field).

Scatter in the observed strength in gypsum sheathed shear walls is relatively large, but perimeter spacing is by far the most influential variable and basic relationships can be observed. Available data is provided in Figure 1 along with a simple empirical expression for strength.



(a) scatter of tested strength vs. perimeter spacing, and strength as simple fit to perimeter spacing



(b) histograms of data against simplified fit (red vertical line) for all perimeter/field fastener conditions available

Figure 1 Test strength of gypsum sheathed shear walls as a function of fastener spacing with predictions

From this data we conclude that the strength of a ½ in. (12.5mm) gypsum sheathed shear wall per side (fully connected to the stud/track or fully strapped and blocked at perimeter) can be predicted by the following empirical expression as a function of perimeter fastener spacing:

$$v_{gyp} = 520 - 25s \text{ (lbf/ft)} \qquad (4a)$$

s = perimeter fastener spacing in in.

$$v_{gyp} = 0.0146[520 - 25(s/25.4)] \text{ (kN/m)} \qquad (4b)$$

s = perimeter fastener spacing in mm

Alternatively, the strength may be presented in tabular form. Given the large variation in Figure 1(b) it is still recommended to use the simplified expression rather than the mean from the test due to anomalies in some of the test data (e.g. walls with boards at 4/4 weaker than 4/12). If this approach is taken the results can be provided as:

Table 5 Nominal shear strength (v_n) per unit length for ½ in. (12.5 mm) gypsum one-sided sheathed walls with studs max 24 in. (600 mm) o.c. a) lbf/ft b) kN/m

Max aspect ratio	Perimeter fastener spacing (in.)					Stud and track (mils)	Screw
	12	8	7	6	4		
2:1	220	320	345	370	420	33	#6

Max aspect ratio	Perimeter fastener spacing (mm)					Stud and track (mils)	Screw
	300	200	175	150	100		
2:1	3.2	4.7	5.0	5.4	6.1	33	#6

Note the data at 12 in. (300 mm) perimeter spacing has the broadest scatter. At this spacing, [22] considered the lateral strength of gypsum sheathed walls with (a) typical lateral detailing such as hold downs or (b) with only bearing wall detailing (see yellow results in Figure 1b). On average the bearing wall detailing had 61% less capacity.

With the gypsum strength prediction available we can now revisit the available shear wall data with finish and assess if the additive strength model is reasonable.

5.2 Additive strength model for shear walls with finish

It is hypothesized that the expected strength, v_e, can be adequately predicted by adding the isolated strength of the finish to that of the "bare" system without finish. This is expressed simply as:

$$v_E = \Omega_b v_n + v_{finish} \qquad (5)$$

where, Ω_b is the expected strength increase of the system (bias) without finish which is ~ 1.1 for WSP and SS sheathed shear walls per Table 1, and $\Omega_b = R_y$ is selected for strap-braced shear walls, though based on the data of Table 2 a larger value could be potentially justified[4]; v_n is the nominal strength from AISI S400; and, v_{finish} is the strength of the gypsum (per length) per the previous section. The expression may be multiplied times the wall length w to be expressed in terms of force (V_e) instead of force/length (v_e). Using Eq. (5) and the predictions from Eq. (4)/Table 5 the expected strength is estimated and compared to available tests in Table 6.

Table 6 Ensemble statistics for cold-formed steel framed sheathed shear walls with finish

	V_{test}/V_e		
Sheathing	mean	COV	n
Oriented Strand Board (OSB) + Gypsum Board	1.00	0.08	8
Strap braced wall[1] + 1 layer Gypsum Board	0.93	0.02	4
Strap braced wall[1] + 2 layer Gypsum Board	1.02	0.03	12
Strap braced wall[1] + Gypsum (All cases)	1.00	0.05	16

1. strap F_{yn}=50ksi (345MPa), R_y=1.1

It is worth noting that the strap-braced wall studies primarily rely on [22] – and in their work an additive model for strength was recommended. The strap-braced walls tested in [22] also considered gypsum board layer(s) installed to resilient channels – the strength increase in this condition was assumed to be zero in the statistics of Table 6, an assumption borne out by the reliability of the V_{test}/V_e ratio and also recommended in [22]. The available data suggests that the additive model, as presented, is a reasonable predictor of expected strength.

6. Consideration of data not in the Shear Wall Database

In [37] a small series of cold-formed steel framed steel sheet sheathed shear walls with and without gypsum board and fiber cement board were recently tested. The ratio of tested strength to strength of the steel sheet sheathing without finish ranged from 1.18 for a single-sided gypsum finish on the opposite side from the steel sheet to 1.79 for fiber cement board added on both sides of the shear wall. The gypsum board added 267 lbf/ft (3.9 kN/m) when installed on the opposing side from the steel sheet and 267+390 lbf/ft (3.9+5.7 kN/m) when added on both sides. Fastener spacing for the gypsum board was at 8 in. (200 mm) and the

[4] To account for frame action in walls with narrow aspect ratio the AISI S400 commentary provides a model for strap-braced walls assuming the stud-to-track connection is fully fixed. This model could be extended to provide a revised overstrength for strap-braced walls, but requires additional analysis and effort that may be unnecessary for walls with finish applied.

observed added strength is well within the expected scatter of Figure 1. The fiber cement board added 452 lbf/ft (6.6 kN/m) installed on the opposite face and 452+705 lbf/ft (6.6+10.3 kN/m) installed on both faces of the wall. Addition of the gypsum or fiber cement board sheathing over the steel sheet sheathing provides additional capacity as buckling of the steel sheet is stabilized. This is not accounted for in the simple additive model of capacity. It is recommended that in the future this beneficial strength be accounted for in the nominal strength since it is derived from the intended energy dissipating mechanism.

In [38] as part of the CFS-NHERI research program (that the first two authors are directly involved in) the team has tested a series of cold-formed steel wall lines that include steel sheet sheathed shear walls with and without gypsum board and Exterior Insulation and Finishing System (EIFS) finish. Wall line specimens are 16 ft (4.9 m) in length and include at least one 4 ft (1.2 m) long steel sheet sheathed shear wall within the wall line. The rest of the wall line includes cold-formed steel framed bearing walls, typically with gypsum board, and tested with and without final finish. Final finish includes installing gypsum board over any steel sheet sheathed shear wall segments and installing EIFS consisting of 5/8 in. (16 mm) glass-mat sheathing with #8 screws at 6 in./16 in. (150 mm/400 mm), foam Board (EPS) layer, base coat and mesh, and a finish coat.

The ratio of the tested strength with and without final finish varies from 1.30 to 1.90 across the specimens. The observed strength increase is not isolated to the shear walls, in fact the largest increase (1.90) occurs when a 16 ft. long wall with a 4 ft. shear wall at one end, is finished for its entire 16 ft (last 12 ft are gypsum sheathed bearing walls) – as has been previously observed in cold-formed steel testing (e.g. the CFS-NEES effort [39]) the lateral contribution of bearing walls is significant and accentuated in the final finished state.

Interpretation of the data for use in expected strength as envisioned herein is complex; however, it is possible to isolate the increase that the EIFS provides. If we assume the lateral strength is additive and we remove the gypsum board increased strength based on Table 5 then the predicted strength contribution from the EIFS is 746 lbf/ft (10.9 kN/m) with a COV of 11% across 4 unique configurations of steel sheet shear walls (the specific specimens are SGGG-1, SGGS-1, SGGS-2, and SWWS-2 where each letter refers to a 4 ft segment of the 16 ft (4.9m) wall line S=shear wall, G=Gypsum bearing wall, W=Window opening in bearing wall, and the final number refers to the anchorage detailing 1=Type 1 and 2=Type 2) and bearing walls within a 16 ft. long wall segment.

7. Upper bound from AISI S400-15 Supplement 1

AISI S400-15 Supplement 1 [1] adopted an upperbound for expected strength based on the work of the firs author. The commentary to AISI S400-15 provides the logic for the selected upperbound:

> "In AISI S400-15 an upperbound (conservative) value for $\Omega_E = \Omega_O$ was employed when additional information for determining Ω_E was unavailable, e.g., in Section E1.3.3. In 2016, a more precise upperbound estimate for Ω_E was recognized. At the design limit, $\phi V_n = V_{be}/R$ where V_{be} is the elastic base shear demand. The expected equilibrium between the demand and capacity is $\Omega_O V_{be}/R = V_n + V_O$, where V_O is the lateral resistance of elements outside of the *seismic force-resisting system* (SFRS). Substituting the design limit for V_n and assuming, as an upperbound, that no force is carried outside of the SFRS (V_O = 0) results in an upperbound estimate of $\Omega_E = \phi\Omega_O$. This upperbound would appear to reward systems with low ϕ (i.e. highly variable). As an additional check, it is considered that the exceedance probability of the upperbound capacity ($\Omega_E V_n$) should be the same as the lowerbound failure probability, assuming a symmetrical probability distribution. This implies: $\Omega_E V_n = V_n + (V_n - \phi V_n)$, or $\Omega_E = 2 - \phi$. Thus, an upperbound is established that $\Omega_E = \max(\phi\Omega_O,\ 2 - \phi)$. This upperbound is applied in this *Standard* when additional information is unavailable for determination of Ω_E."

For the SS and WSP sheathed shear walls ϕ=0.6, $\Omega_o = 3$, and the resulting Ω_E upperbound is 1.8. For the strap-braced walls ϕ=0.9, $\Omega_o = 2$, and the resulting Ω_E upperbound is again 1.8. It is recommended that these upperbounds be maintained in any new expected strength provisions.

8. Recommendations for AISI S400

Based on the analysis herein the following is recommended for the expected strength factor:

$$\Omega_E = \frac{\Omega_b v_n + v_{finish}}{v_n} \leq \max\,(\phi\Omega_o, 2 - \phi) \qquad (6)$$

Table 7 Parameters for expected strength factor determination

System	Ω_b	v_n	v_{finish}	ϕ	Ω_o
WSP	1.1	Table E1.3-1	Mean shear strength/unit length of finish, not less than $0.1v_n$	0.6	3
SS	1.1	Table E2.3-1 or Section E2.3.1.1.1	Mean shear strength/unit length of finish, not less than $0.1v_n$	0.6	3
Strap-braced	R_y	Eq. E3.3.1-1/w	Mean shear strength/unit length of finish, not less than $0.2v_n$	0.9	1.8

The lowerbounds on v_{finish} are based on judgment, in that nearly all walls must be finished and any additional attachment tends to add some strength. The lower-bound value for strap-braced walls is set higher than WSP or SS to recognize that the strength of bare strap-braced walls commonly exceeded R_y for F_{yn}=50 ksi (345 MPa) strap as shown in Table 2. (Note from Table 6 that walls with strap and gypsum finish did not require Ω_b to be greater than R_y).

Definitive strength predictions for finish systems are not widely available. Engineers must exercise judgment; however, some guidance is possible. For a single layer of 1/2 in. (12.5 mm) gypsum board attached on its perimeter to the stud and track of a shear wall, or to strapping in-line blocked in the wall Eq. 4a/4b or Table 5 are recommended.

Multiple layers or multiple sides of gypsum board may be approximated by adding the strength of each board. If the gypsum board is not blocked the strength reduction factor of 0.35 utilized in AISI S400-15 E5.4.1.1(t) is recommended. If the gypsum board is isolated through attachment to resilient channels it is recommended to ignore any contribution from the gypsum board (consistent with observations here and [22]). The values provided here, developed for ½ in. (12.5 mm) gypsum board, may reasonably be extended to 5/8 in. (16 mm) gypsum board.

For EIFS systems, as reported herein, in one study across 4 tests, the estimated strength increase for a layer of fully finished EIFS was 746 lbf/ft (10.9 kN/m). ASCE 41-17 [recommends a value of 150 lbf/ft (2.2 kN/m) for plaster on metal lath over cold-formed steel framing. In addition, ASCE 41-17 [40] Table 12-1 for wood framing recommends 350 lbf/ft (5.1 kN/m) for stucco, 70-500 lbft/ft (1.0-7.3 kN/m) for wood siding, and 80-400 lbf/ft (1.2-5.8 kN/m) for gypsum plaster.

9. Example (Imperial Units only)

Consider a 12 ft long single-sided steel sheet sheathed shear wall with 0.030 in. sheet fastened at 4 in. on its perimeter. Relevant finish for the well is ½ in. gypsum fastened at 12/12 to both sides. On the interior face, without the steel sheet, the gypsum board is run perpendicular to the studs and unblocked. Determine the expected strength factor Ω_E for capacity-based design.

$$\Omega_E = \frac{\Omega_b v_n + v_{finish}}{v_n} \leq \max\left(\phi\Omega_o, 2-\phi\right) \tag{7}$$

Ω_b=1.1 for SS [Table 7]
v_n=1170 lbf/ft per S400-15/S1-16, Table E2.3-1
v_{finish}=220 lbf/ft + 0.35(220) lbf/ft = 297 lbf/ft
(note, OK b/c > 0.1v_n=117 lbf/ft) [Table 8]
$\max(\phi\Omega_o, 2-\phi) = \max(0.6 \cdot 3, 2-0.6) = 1.8$

$$\Omega_E = \frac{1.1 \cdot 1170\frac{lbf}{ft} + 297\frac{lbf}{ft}}{1170\frac{lbf}{ft}} \leq 1.8 \tag{8}$$

$$\Omega_E = 1.35 \tag{9}$$

This calculated $\Omega_E = 1.35$ is considerably less than the 1.8 currently required in AISI S400 and would therefore lead to more economical design for capacity-protected elements such as chord studs.

10. Conclusions

Capacity-based seismic design is intended to ensure reliable performance of the energy dissipating mechanism in a seismic force resisting system by designing components in the load path, but not part of the intended mechanism, at the expected strength of the energy dissipating mechanism. AISI S400 provides complete seismic provisions for cold-formed steel framed strap-braced and sheathed shear walls. The expected strength factor utilized in current design in AISI S400 is an upperbound approximation. Utilizing a large database of tested shear walls new factors were developed for the expected strength of CFS framed walls. Finish systems on the walls (e.g. gypsum board) have a large impact on the observed strength and a simple additive model was found to provide a reliable prediction for expected strength of walls with finish. This additive model is recommended for use in CFS seismic design and shown to provide a more efficient prediction for expected strength.

11. Acknowledgments and Disclaimer

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