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Effective Strip Model for Cold-Formed Steel Shear Wall using Steel Sheet Sheathing

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Abstract

The cold-formed steel framed shear wall sheathed with steel sheets (CFS-SSSW) is a code approved lateral force resisting system for light-framed buildings. The current design approach for cold-formed steel shear walls in U.S. is based on full-scale tests. The AISI Lateral Design Standard provides nominal shear strength for limited wall configurations. This paper presents an analytical design method – the Effective Strip Method for predicting the nominal strength of CFS-SSSWs for both wind and seismic design. The proposed design approach is based on a tension field action model of the sheathing with additional consideration of the sheathing fastener strength, the fastener spacing, the wall aspect ratio, and the material properties. A total of 142 full scale tests are used to verify the proposed design method and the supporting design equations. It shows that the proposed method has a good agreement with the test results. The Effective Strip Method is an alternate approach to determine the nominal strength of CFS-SSSWs without conducting full-scale shear wall tests.

1. Introduction

Lateral force resisting systems in CFS light-framed construction commonly employ CFS framed shear walls sheathed with steel sheets or wood based panels. Fig. 1 shows a typical 8 ft. by 4 ft. CFS shear wall with sheathing. The sheathing is usually fastened to the frame around boundary elements and an inner stud by self-drilling screws. Hold-downs are commonly used in CFS shear walls to resist the overturning forces. The International Building Code (IBC 2006) and the North American Standard for Cold-Formed Steel Framing – Lateral Design (AISI S213-07) provide provisions for CFS shear walls using three types of sheathing materials: 15/32 in. Structural 1 plywood, 7/16 in. OSB, and 0.018 in. and 0.027 in. steel sheet. Those published values are based on research projects by Serrette et al (1996, 1997, and 2002).

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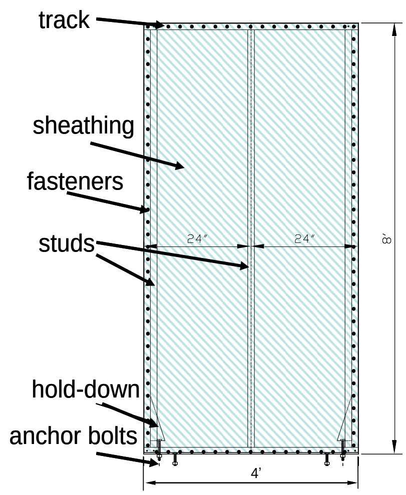

Figure 1: Components in a typical CFS shear wall

The current CFS design provisions are capacity based design and provide no analytical methodology to predict the shear resistances of CFS shear walls. Instead, those provisions only provide nominal shear strength for specified and limited wall configurations. Fig. 2 shows the table of nominal strength for wind loads from AISI S213 (2007). The table is also adopted by IBC (2006). The wind load table requires the fastener size to be minimum No. 8. AISI S213 also provides a similar table for seismic design. It can be seen that the current design specifications offer the structural engineers limited options in the sheathing materials, sheathing thickness, wall aspect ratios, etc. No analytical models or design equations have been developed for predicting the shear strength. On the other hands, closed-form design equations for the hot-rolled steel plate shear wall (SPSW) and reinforced concrete shear wall have been developed and adopted by design documents (AISC Seismic Design Manual, 2005; ACI Building Code Requirements 318, 2005).

United States and Mexico

Nominal Shear Strength (R_n) for Wind and Other In-Plane Loads for Shear Walls [1,4,6,7,8]

(Pounds Per Foot)

Assembly Description	Maximum Aspect Ratio (h/w)	Fastener Spacing at Panel Edges[2] (inches)			
		6	4	3	2
15/32" structural 1 sheathing (4-ply), one side	2:1	1065 [3]	-	-	-
7/16" rated sheathing (OSB), one side	2:1	910 [3]	1410	1735	1910
7/16" rated sheathing (OSB), one side oriented perpendicular to framing	2:1	1020	-	-	-
7/16" rated sheathing (OSB), one side	2:1 [5]	-	1025	1425	1825
0.018" steel sheet, one side	2:1	485	-	-	-
0.027" steel sheet, one side	4:1	-	1,000	1085	1170

Figure 2: Nominal shear strength table in AISI S213 (Courtesy of AISI)

The hot-rolled steel plate shear wall has been studied experimentally and analytically by a number of researchers (Thorburn et al., 1983; Timler and Kulak, 1983; Tromposch and Kulak, 1987; Roberts and Sabouri-Ghomi, 1992; Sabouri-Ghomi and Roberts, 1992; Cassese et al., 1993; Elgaaly et al., 1993; Driver et al., 1998; Elgaaly and Liu, 1997; Elgaaly 1998; Rezai, 1999; Lubell et al., 2000; Berman and Bruneau, 2004, Vian and Bruneau, 2004). Based on the elastic strain energy assumption, Thorburn et al. (1983) developed an analytical model known as a strip model (Fig. 3) to predict the shear strength of SPSW. The strip model based design equations were later refined by Timler and Kulak (1983) and Berman and Bruneau (2003). The strip model was adopted by BSSC (2004) and AISC (2005).

CFS-SSSW behaves to some extent similar to SPSW: both structures demonstrate out-of-plane shear buckling in the sheathing/infill plate. However the infill plate is usually welded to the boundary elements of SPSW while CFS sheathing is generally fastened to the boundary elements by self-drilling screws or pins. Besides the sheathing shear buckling, other failure modes including fastener pull-out, fastener pull-over, and sheathing tear at fasteners also affect the shear strength of CFS-SSSWs. Therefore, the strip model will not work for CFS-SSSWS. The new analytical model for CFS-SSSWs shall consider the sheathing tensile strength, the fastener strength at the panel edges, and the framing member configurations.

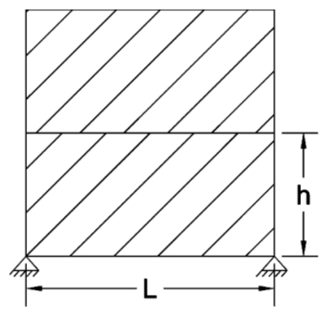

Figure 3: Strip model for SPSW

2. Analytical Model for CFS-SSSW – Effective Strip Model

Extensive experimental investigation on CFS-SSSWs was carried out by Serrette et al (1996, 1997, and 2002), Yu et al. (2007, 2009), and Balh (2010). Fig. 4 shows the tension field action in CFS-SSSWs with different aspect ratios in Yu et al. (2007. 2009). It was found that the shear resistance of CFS-SSSWs was primarily provided by the steel sheathing through the diagonal tension field action. The observed failure modes were screw connection failure within the diagonal tension field and in some cases, boundary stud buckling due to overturning forces. As illustrated in Fig. 4, the steel sheathing is not contributing to the shear resistance equally across the width of the entire shear wall. There was a certain width of the sheathing that was accountable for conveying most of the tension force in the system. Also, in most tested wall specimens, sheathing-to-framing connection failure occurred at the corners of the shear walls usually inside the observed tension field. This observation led to the creation of the effective strip model for predicting the shear strength of CFS-SSSWs as illustrated in Fig. 5. In the effective strip model, it is assumed that a particular width of the sheathing in the diagonal direction – the effective strip is engaged in the tension field action to provide shear resistance to the lateral force which is applied to the top of the wall.

Figure 4: Tension field action of CFS-SSSWs

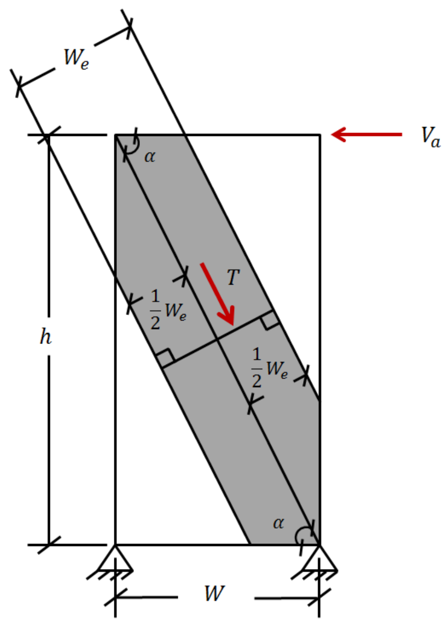

Figure 5: Effective strip model of steel sheet sheathing

In Fig. 5, V_a is the applied lateral load, T is the resulting tension force in the effective strip of the sheathing, and h and W are the height and the width of the wall respectively. α is the angle at which the tension force is acting. W_e is the width of the effective strip that is accountable for conveying all the tension force in the system and is defined in a way that it is perpendicular to the direction of the strip. It is assumed that the effective strip is centered to the diagonal line from the corner to the other corner of the wall. Based on the effective strip model, the applied lateral load V_a can be expressed in the following equation.

$$V_a = T \cos \alpha \tag{1a}$$

In this model, the applied lateral load is directly related to the tension force experienced in the effective strip of the steel sheet sheathing. In other words, the maximum force obtained from shear wall system is limited by the maximum tension force in the sheathing. The maximum tension force in the sheathing is then limited by capacities of two components in the system. The first component is the capacity of sheathing-to-framing connection at both ends of the effective strip (e.g. the corners of shear walls inside the effective tension field). The second component is the material yield strength of the effective strip. The yielding of the sheathing material was not observed in the actual experimental investigation by Yu (2007, 2009). However, this type of failure mode could possibly happen when a large number of fasteners are used to connect the sheathing to the CFS frame. Thus, the nominal shear force in a CFS-SSSW can be determined as follows.

$$V_n = T_n \cos\alpha \tag{1b}$$

where V_n is the nominal shear strength of a CFS-SSSW and T_n is the nominal tension strength of the effective strip of the sheathing. As previously discussed, the nominal tension force is determined as follows.

$$T_n = minimum\{\textstyle\sum_{i=1}^{n} P_{nsi}\,, W_e t_{sh} F_y\}, \tag{2}$$

where P_{ns} is the nominal shear strength of individual sheathing-to-framing connection, t_{sh} is the sheathing thickness, F_y is the sheathing yield stress, and n is the total number of fasteners at one end of the effective strip. It shall be noted that the proposed model assumes the fastener configurations are same at both ends of the effective strip. Nominal shear strength of fastener connections is limited by three types of failure mechanisms. The first is connection shear limited by tilting and bearing. The second is connection shear limited by end distance measured in line of force from center of a standard hole to the nearest end of connected parts. The third is shear failure in screws. An expanded version of Eq. 2 can be expressed in Eq. 3 which considers the framing details of CFS-SSSWs.

$$T_n = minimum\ \left\{n_t P_{ns,t} + n_s P_{ns,s} + P_{ns,t\&s}, W_e t_{sh} F_y\right\} \tag{3}$$

where n_t is the number of fasteners on the track within the effective strip at one end, n_s is the number of fasteners on the boundary studs within the effective strip at one end, P_{ns} is the nominal shear strength of the fasteners, the subscript t and s are regarding connections on track and stud respectively, and the subscript t and s is regarding a fastener at the corner of the wall at which its fastener is penetrating through sheathing, track, and stud. Fig. 6 illustrates the equilibrium of the tension force in sheathing and the sum of connection shear strength.

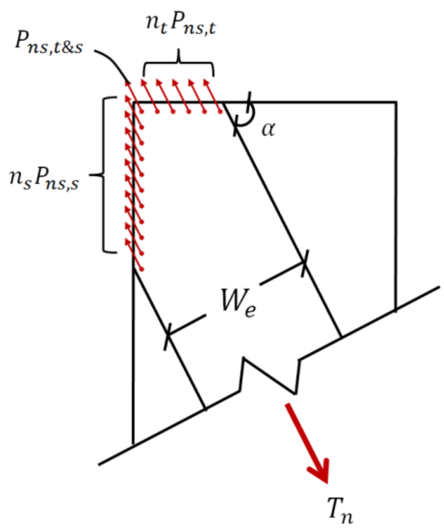

Figure 6: Equilibrium of nominal tension force in sheathing and sum of nominal connection shear capacity

The nominal shear strength of a CFS-SSSW can be expressed in terms of the number of sheathing-to-framing connections and nominal connection shear strength within its effective strip width as follows.

$$V_n = \text{minimum}\left\{(n_t P_{ns,t} + n_s P_{ns,s} + P_{ns,t\&s}) \cos\alpha, W_e t F_y \cos\alpha\right\} \tag{4}$$

Eq. 4 summarizes the proposed effective strip model for predicting the nominal shear strength of a CFS-SSSW. Due to the geometry shown in Fig. 7, the number of connections can be related to the width of the effective strip.

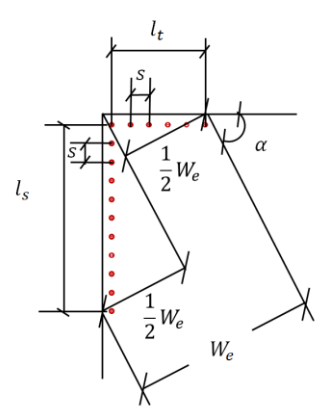

Figure 7: Sheathing-to-framing fastener connection layout within effective strip

In Fig. 7, s is the fastener spacing (it is assumed that the fastener spacing is uniform on the panel edges) and l_t is the approximate length on track that is contributing to the effective tension strip determined by the product of the number of fasteners on track within its effective width and the fastener spacing. Likewise, l_s is the approximate contributing length on stud and determined by the product of the number of fasteners on stud within its effective width and the fastener spacing. The effective strip width of sheathing can be expressed as follows.

$$W_e = 2l_t \sin\alpha = 2sn_t \sin\alpha \text{ or } W_e = 2l_s \cos\alpha = 2sn_s \cos\alpha \tag{5}$$

In these equations, the short distances of the fastener at the corner to the outer face of stud and to the outer face of track are not included in l_t and l_s respectively. Inclusion of these short distances will complicate the equations, and also, the deviations due to the exclusion of these short distances are considered to be minimal. Also, the number of the fasteners on track within its effective width can be described as following equations.

$$n_t = \frac{W_e}{2s\sin\alpha} \tag{6}$$

Likewise, the number of fasteners on stud can be expressed in the form of the following as well.

$$n_s = \frac{W_e}{2s\cos\alpha} \tag{7}$$

Note that the number of fasteners on stud to the number of fasteners on track ratio gives the tangent of an angle α, which is the height to width aspect ratio of the shear wall. Substituting the number of fasteners on track and stud within its effective width to the previously defined equation of nominal shear strength of a CFS-SSSW, the equation becomes as follows.

$$V_n = \text{minimum } \left\{ \left(\frac{W_e}{2s\sin\alpha} P_{ns,t} + \frac{W_e}{2s\cos\alpha} P_{ns,s} + P_{ns,t\&s}\right)\cos\alpha, W_e t_{sh} F_y \cos\alpha \right\} \tag{8}$$

Eq. 8 indicates that the key factor in the effective strip model is the determination of the effective strip width, W_e.

3. Design Formula for Effective Strip Width

Based on the proposed effective strip model, the nominal shear strength of a CFS-SSSW can be calculated in terms of nominal shear capacities of sheathing-to-framing connections and the yield strength of the effective strip once the effective width of the tension strip is determined. Experimental data of 142 monotonic and cyclic full-scale shear wall tests of CFS-SSSWs from Yu et al. (2007, 2009) and Balh (2010) are used to develop and verify design equations of the effective strip width. In those tests, the material properties of test specimens were verified and reported. In this research, the actual measurement of the material thicknesses and mechanical properties were adopted to develop the design formula of the effective strip.

The proposed formula for the effective strip width is listed in Eqs. (9).

$$W_e = \begin{cases} W_{max}, if\ \lambda \le 0.0819 \\ \rho W_{max}, if \lambda > 0.0819 \end{cases} \tag{9}$$

where

W_{max} = maximum width of effective strip as illustrated in Fig. 8,

$W_{max} = \frac{W}{\sin\alpha}$

$$\rho = \frac{1 - 0.55(\lambda - 0.08)^{0.12}}{\lambda^{0.12}} \tag{10}$$

$$\lambda = 1.736 \frac{\alpha_1 \alpha_2}{\beta_1 \beta_2 {\beta_3}^2 a} \tag{11}$$

a = Aspect ratio of a shear wall (height / width)
$\alpha_1 = F_{ush}/45$
$\alpha_2 = F_{umin}/45$
$\beta_1 = t_{sh}/0.018$
$\beta_2 = t_{min}/0.018$
$\beta_3 = s/6$
F_{ush} = Tensile strength of steel sheet sheathing in ksi
F_{umin} = Controlling tensile strength of framing materials in ksi (smaller tensile strength of track and stud)
t_{sh} = Thickness of steel sheet sheathing in inches
t_{min} = Smaller of thicknesses of track and stud in inches
s = fastener spacing on the panel edges, Note that the fastener spacing on track and stud are assumed to be equivalent.

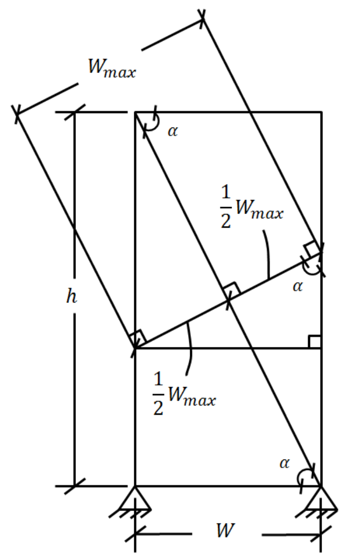

Figure 8: Maximum width of the effective strip

Fig. 9 shows a comparison between the proposed formulas of effective strip width with the experimental results. A total of 142 tests, including 70 monotonic and 72 cyclic, are included in the analysis. The 142 tests cover a large range of variations in the wall configurations including framing thickness 33 mil to 54 mil, steel sheathing thickness 18 mil to 33 mil, fastener spacing 2 inches to 6 inches, and wall aspect ratio 1.0 to 4.0. Based on the proposed effective strip model, the actual effective strip width, $W_{e,test}$ for each test can be determined using Eq. 12.

$$W_{e,test} = \text{maximum}\left\{\frac{2s(V_{test}\sin\alpha - P_{ns,t\&s}\sin\alpha\cos\alpha)}{P_{ns,t}\cos\alpha + P_{ns,s}\sin\alpha}, \frac{V_{test}}{t_{sh}F_y\cos\alpha}\right\} \tag{12}$$

where V_{test} is the peak load obtained from each shear wall test, and all the other notations are previously defined.

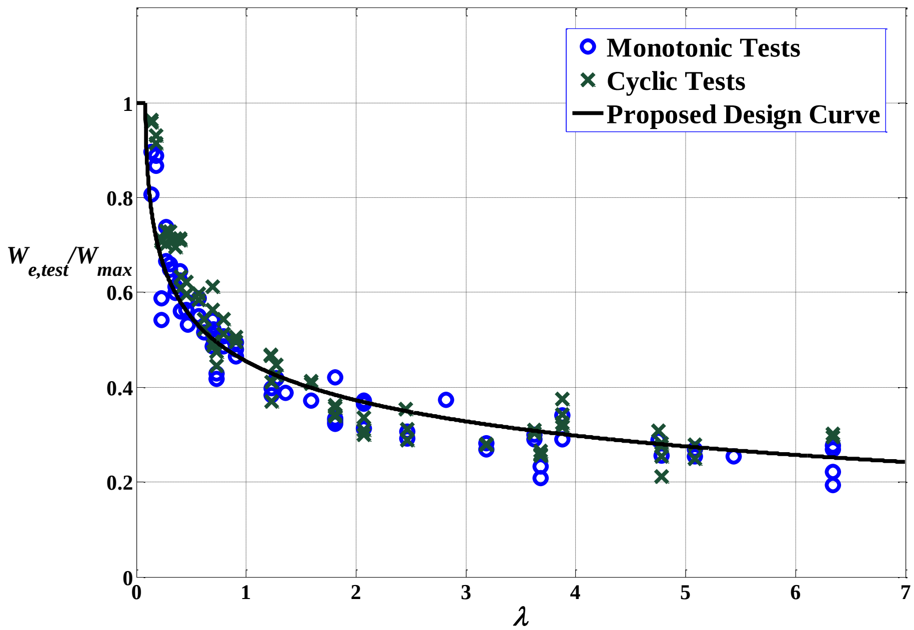

Figure 9: Comparison between the proposed design curve with test results

Fig. 9 indicates that the proposed effective strip model and the design formula for the effective strip width work well for the CFS-SSSWs. It also shows that the CFS-SSSWs demonstrate similar peak loads for monotonic and cyclic loading. Therefore, the proposed analytical model can be used for both wind load and seismic load design. As mentioned earlier, the proposed design equations to determine the effective strip width are developed by using actual material properties of the framing members. However, these properties are usually not readily accessible by design engineers. In order to allow the use of nominal material properties in the proposed design method, further analyses were carried out. Fig. 10 shows the comparison between the proposed design curve with test results when nominal mechanical properties and design thickness of steels are used to determine the effective strip width.

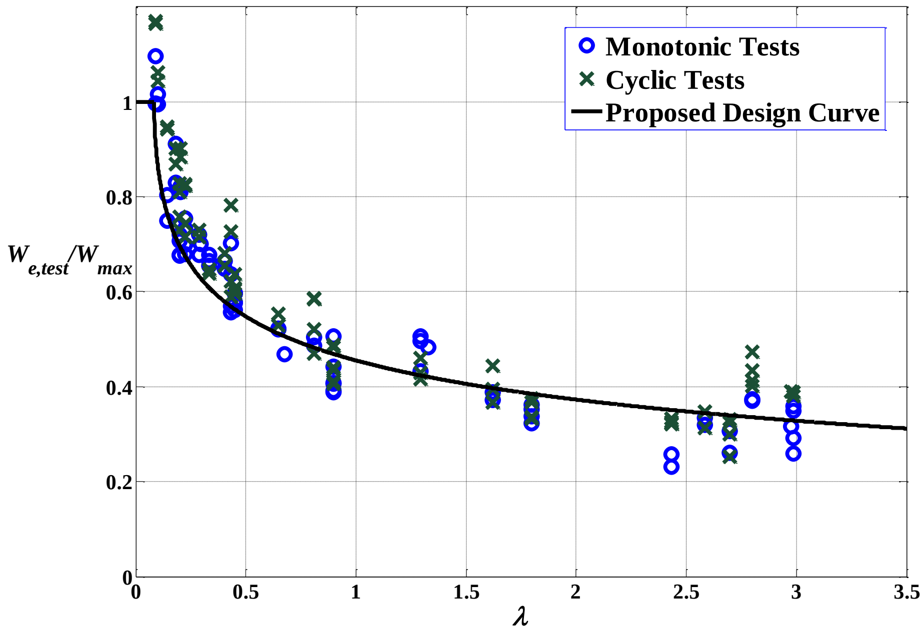

Figure 10: Comparison between the proposed design curve with test results (Nominal)

When using nominal and design material properties, the proposed design equation is still able to capture the trend of the test data. Compared to Fig. 9, in Fig. 10, most of the test data points are slightly above the design curve. It indicates that when using nominal and design material properties, the design equation yields a slightly conservative result compared to using the actual material properties. However the difference is not significant enough to require a different equation for W_e. The statistics of the comparisons is listed in Table 1. The results indicate that the use of nominal material properties in the proposed effective width method will yield 2.2% more conservative results with 15% greater variation than the results by using actual material properties. Those differences will be considered in the resistance factor calculation described in the following section.

Table 1: Statistical analysis results for the proposed design equation

Material Property	No. of tests	V_{Test}/V_{Design}		
		Avg.	Std. dev.	COV
Actual	142	1.000	0.114	0.114
Nominal	142	1.022	0.133	0.131

4. Discussion

The proposed effective strip model and design equations suggest that the effective strip width is controlled by the framing and sheathing's thickness and tensile strength, fastener spacing, and the wall's aspect ratio. The proposed analytical model can be used to predict the shear capacity of the CFS-SSSWs without failures in boundary studs or hold-downs. The failures in boundary studs and hold-downs shall be successfully prevented if the designers follow the design guidance by AISI S213 (2007) which requires that the chord studs and uplift anchorage have the nominal strength to resist the lesser of the load that the system can deliver or the amplified seismic load.

It also shall be noted that the AISI S213 (2007) requires a reduction factor be used for CFS shear walls with an aspect ratio greater than 2:1 but not exceeding 4:1. The proposed effective strip model produces the nominal strength without aspect ratio reduction for slender walls. Therefore the reduction factor in AISI S213 applies to the results by the proposed design approach for CFS shear walls with an aspect ratio greater than 2:1.

In order to confirm the validity of the effective strip model and the design equations for the effective strip width, the published nominal shear strength of CFS sheet steel shear walls from Table C2.1-1 (wind) and Table C2.1-3 (seismic) in AISI S213 (2007) are used to compare with the nominal shear strength values calculated by the proposed approach. A total of eight shear wall configurations are analyzed. Table 2 shows the comparison.

Table 2: Comparison of nominal shear strength values

Shear wall Configuration	AISI S213 (2007) Table C2.1-1 (plf)	AISI S213 (2007) Table C2.1-3 (plf)	Predicted V_n (plf)
2:1x33x18-6	485	390	399
4:1x43x27-4	1000	1000	785
4:1x43x27-3	1085	1085	891
4:1x43x27-2	1170	1170	1064
2:1x33x27-6	647	647	597
2:1x33x27-4	710	710	712
2:1x33x27-3	778	778	803
2:1x33x27-2	845	845	935
Note: minimum screw size No. 8 for all configurations.			

In Table 2, the first column from the left lists all the wall configurations included in AISI S213 (2007), the second and third columns list the published nominal shear strength of CFS steel sheet shear walls for wind and seismic loads respectively, and the fourth column lists the nominal shear strength values for each shear wall configuration estimated by the effective strip model. The definition of the wall configuration symbol is illustrated in Fig. 12.

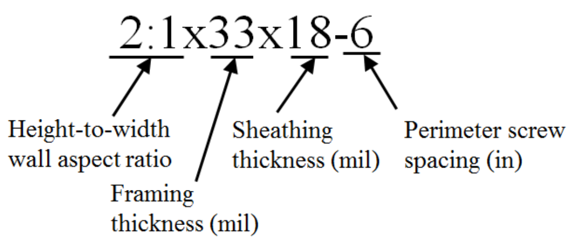

Figure 12: Definition of shear wall configuration

The grade of steel sheet sheathing and framing members is considered to be ASTM A1003 Grade 33, having minimum yield stress of 33 ksi and tensile strength of 45 ksi. The sheathing-to-framing fastener size is No. 8 as specified in AISI S213 (2007). Nominal values are used for sheathing and framing material tensile strengths and screw diameters, and design values are used for sheathing and framing thicknesses to determine the nominal shear strength of each wall configuration.

According to the results shown in Table 2, most of the estimated nominal shear strength values are a little conservative or almost equivalent to the published values. Also, the developed analytical model is able to capture the trends of the impacts of the key parameters (e.g. screw spacing, framing and sheathing material thickness, etc) to the shear wall strength.

A reliability analysis was also carried out to assess the proposed design approach by following the provisions in Chapter F of AISI S100 (2007). The resistance factors, ϕ, for LRFD design can be determined in accordance with AISI S100 (2007) with a target reliability index, β, of 2.5. The resistance factor, ϕ, can be determined as Eq. 13.

$$\phi = C_\phi (M_m F_m P_m) e^{-\beta\sqrt{V_M^2 + V_F^2 + C_P V_P^2 + V_Q^2}} \tag{13}$$

where:
C_ϕ = Calibration coefficient (1.52 for LRFD);
M_m = Mean value of material factor (1.0 for actual, 1.178 for nominal);
F_m = Mean value of fabrication factor (1.0 for actual, 0.965 for nominal);
P_m = Mean value of professional factor (1.000 for actual and 1.022 for nominal);
e = Natural logarithmic base (2.718);
β = Target reliability index (2.5);
V_M = Coefficient of variation of material factor (0.1 for actual, 0.085 for nominal);
V_F = Coefficient of variation of fabrication factor (0.05 for actual, 0.053 for nominal);
C_p = Correction factor (1.022);
V_P = Coefficient of variation of test results (0.114 for actual and 0.131 for nominal);
V_Q = Coefficient of variation of load factor (0.21 for LRFD).

For the case in which actual material properties (yield stress, tensile strength, thickness) are used (actual case), the values of M_m, V_M, F_m, and V_F were taken from Table F1 in AISI S100 (2007) for “Structural Members Not Listed Above”. For the case in which nominal and design material properties were adopted (nominal case), the values of M_m and V_M were determined by taking the mean and the coefficient of variation of the ratios between the actual mechanical properties and the nominal mechanical properties of the materials used in the 142 specimens. Similarly, the factors regarding the effect of fabrication, F_m and V_F for the nominal case were determined by taking the mean and the coefficient of variation of the ratio between the actual thickness and the design thickness of the materials used in the 142 specimens. According to the reliability analysis, the resistance factors are 0.79 for the actual case and 0.90 for the nominal case. Thus, it is recommended that the resistance factor of 0.79 be used when actual material properties are used in the design and the resistance factor of 0.90 be used when nominal and design material properties are used instead. The AISI S213 (2007) adopts an LRFD resistance factor of 0.65 for wind load design and 0.60 for seismic design. The developed analytical model offers an accurate and reliable method to predict the nominal strength of CFS-SSSWs. The new approach provides designers an analytical way of determining the shear wall capacities without carrying out full-scale physical testing.

5. Conclusion

An analytical model – Effective Strip Model is proposed in this paper to predict the nominal strength of CFS-SSSWs. The proposed design approach shows consistent agreements with experimental results. The design equations are developed by using actual material and mechanical properties of the framing members. Further analyses show that the nominal material properties can also be used in the proposed equations to produce reliable shear wall strength. The resistance factors are developed for both cases. The proposed design method, Effective Strip Method, provide designers an analytical tool to determine the nominal strength of CFS-SSSWs without conducting full-scale shear wall tests.

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