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Abstract

The cold-formed steel framed shear wall sheathed with steel sheet sheathing (CFS-SSSW) is a code approved lateral force resisting system for light framed construction. The AISI Steel Framing Standards – Lateral Design (AISI S213-07) provides design provisions for CFS-SSSW. The development of the nominal strength of CFS-SSSW in AISI S213 was based on full-scale experiments which were subjected to limitations in both wall configurations and material properties. This paper presents an analytical model – the Effective Strip Model developed for predicting the nominal strength of CFS-SSSWs. The proposed analytical model and supporting design equations are further verified by experimental results. The proposed design approach shows good agreements with test results. The statistical assessment indicates that the new design method is reliable and providing designers an alternate tool to determine the capacity of CFS-SSSWs besides conducting full-scale physical shear wall testing.

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1. Introduction

Lateral force resisting systems in CFS constructions usually employ CFS framed shear walls sheathed with steel sheets or wood based panels. Figure 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 interior stud by self-drilling screws. Hold-downs are commonly used in CFS shear walls to resist the overturning forces. Figure 2 shows a three-story residential building using CFS-SSSWs. 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 done by Serrette et al (1996, 1997, and 2002).

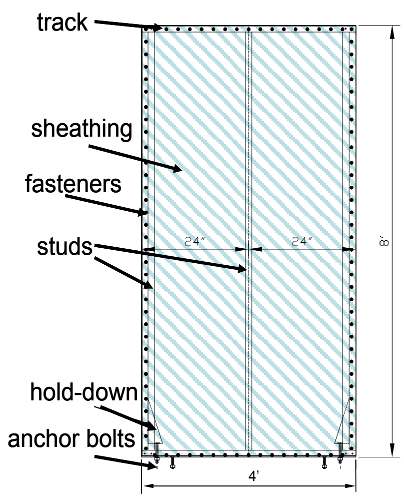

Figure 1: Components in a typical CFS shear wall

Figure 2: CFS shear walls using sheet steel sheathing (Courtesy of Simpson Strong Tie)

The current CFS design provisions are capacity based design and provide no rational methodology to predict the shear resistances of CFS shear walls. Instead, those provisions only provide nominal shear strength for specified and limited wall configurations. Figure 3 shows the table of nominal strength for wind loads from AISI S213 (2007). The table is also fully adopted by IBC (2003, 2006). The wind load table requires the fastener size to be minimum No. 8. AISI S213 and IBC also provide a similar table for seismic design. It can be seen that the current codes give 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 3: 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 an elastic strain energy assumption, Thorburn et al. (1983) developed an analytical model known as a strip model (Figure 4) to predict the shear strength of SPSW. The strip model based design equations were latterly refined by Timler and Kulak (1983) and Berman and Bruneau (2003). The strip model was adopted by BSSC (2004) and AISC (2005).

CFS-SSSW has some similar behaviors as 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. Apart from the sheathing shear buckling, other failure modes including fastener pull-out, fastener pull-over, and the sheathing tear at fasteners also affect the shear strength of CFS-SSSWs. Therefore, the analytical model for CFS-SSSWs shall consider the sheathing tensile strength, the fastener strength at the panel edges and the framing member configurations.

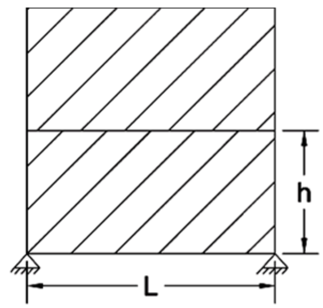

Figure 4: Strip model for SPSW

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

Extensive experimental investigation on CFS-SSSWs was carried out in Yu et al. (2007, 2009). Figure 5 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 are screw connection failures within the diagonal tension field and in some cases, boundary stud buckling due to overturning forces. As illustrated in Figure 5, 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 lead to the creation of the effective strip model for predicting the shear strength of CFS-SSSWs as illustrated in Figure 6. 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.

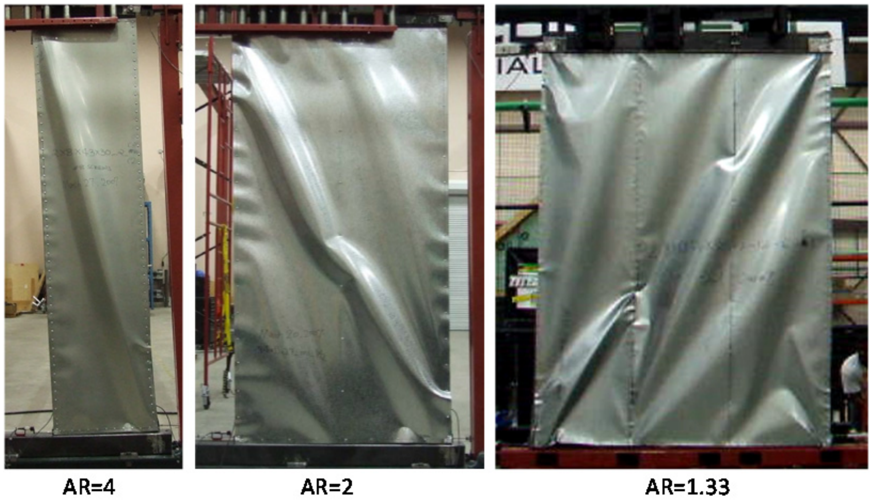

Figure 5: Tension field action of CFS-SSSWs

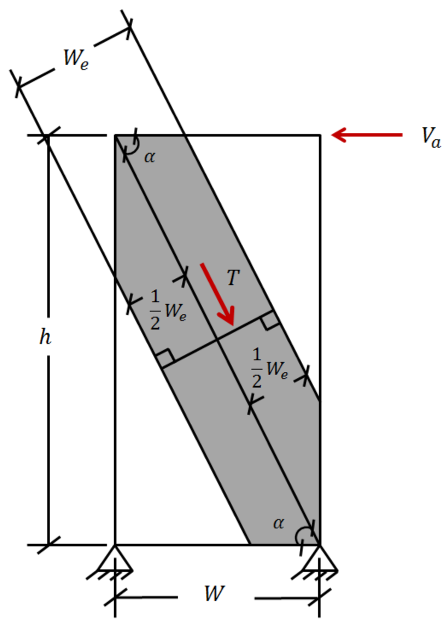

Figure 6: Effective strip model of steel sheet sheathing

In Figure 6, 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 is 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.

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

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. The nominal tension force T_n is determined as the smaller of the sum of the nominal shear strengths of sheathing-to-framing connections and the material yield stress of the effective strip of sheathing.

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 screw.

An expanded version of Eq. 2 can be expressed in Eq. 3 which considers the framing details of CFS-SSSWs.

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

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 $t\&s$ is regarding a fastener at the corner of the wall at which its fastener is penetrating through sheathing, track, and stud. Figure 7 illustrates the equilibrium of the tension force in sheathing and the sum of connection shear strength.

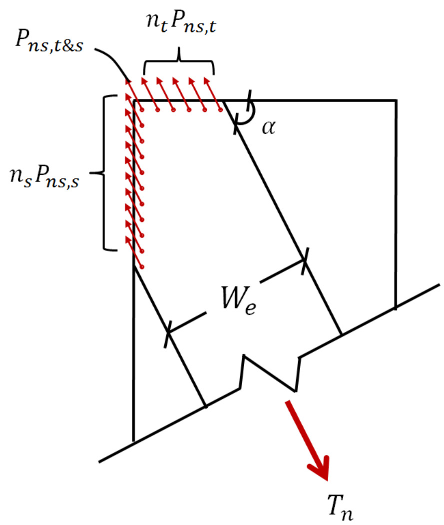

Figure 7: Equilibrium of nominal tension force in sheathing and sum of nominal connection shear capacity

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.

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

Eq. 4 summarizes the proposed effective strip model for predicting the nominal shear strength of a CFS-SSSW. Due to the geometry shown in Figure 8, the number of connections can be related to the width of the effective strip.

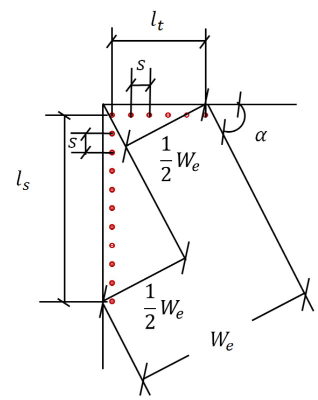

Figure 8: Sheathing-to-framing fastener connection layout within effective strip

In Figure 8, 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.

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

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.

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

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 tensile strength of the effective strip once the effective width of the tension strip is determined. Experimental data of more than 140 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).

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

where

W_{max}= maximum width of effective strip as illustrated in Figure 9, $W_{max} = \frac{W}{\sin\alpha}$

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

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

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.

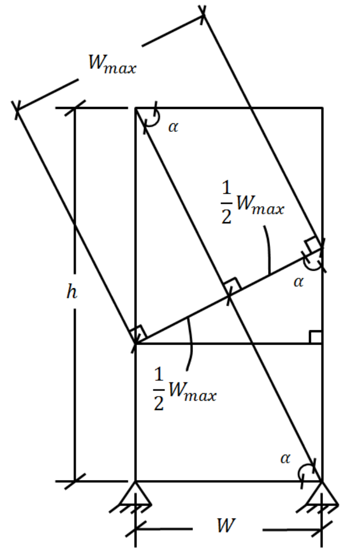

Figure 9: Maximum width of the effective strip

Figure 10 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 68 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.

$$W_{e,test} = \text{maximum}\left\{\frac{2s(V_p \sin\alpha - P_{ns,t\&s}\sin\alpha\cos\alpha)}{P_{ns,t}\cos\alpha + P_{ns,s}\sin\alpha}, \frac{V_p}{tF_y\cos\alpha}\right\} \quad (12)$$

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

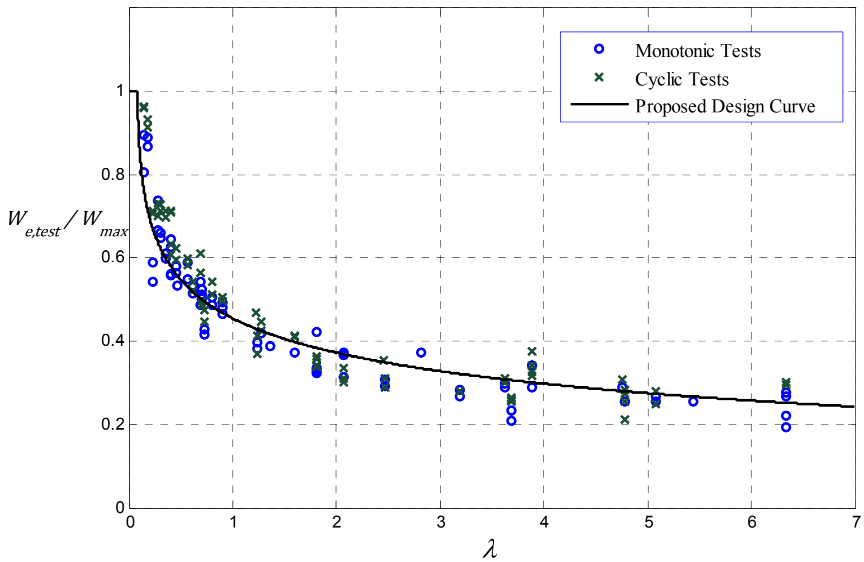

Figure 10: Comparison between the proposed design curve with test results

Figure 10 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. The statistics of the comparison is listed in Table 1.

Table 1: Statistical analysis results for the proposed design equation

No. of tests	$\rho_{Test}/\rho_{Design}$		
	Avg.	Std. dev.	COV
142	1.005	0.121	0.121

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 shall be noted that the development of the proposed design approach is based on actual thicknesses and mechanical properties of the test specimens. Also, it has been found that the actual mechanical properties of specimens are generally greater than the nominal or the design values specified by the industry.

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	375
4:1x43x27-4	1000	1000	732
4:1x43x27-3	1085	1085	831
4:1x43x27-2	1170	1170	990
2:1x33x27-6	647	647	547
2:1x33x27-4	710	710	652
2:1x33x27-3	778	778	734
2:1x33x27-2	845	845	851
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 Figure 11.

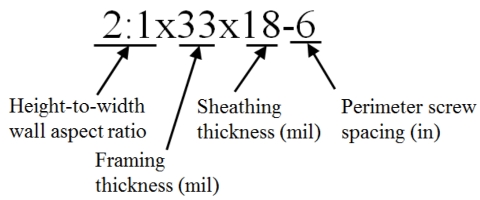

Figure 11: Definition of shear wall configuration

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 thicknesses, sheathing and framing material tensile strengths, and screw diameters 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 less than the published values but fairly close. The differences are primarily contributed by the use of nominal material properties in the design equations. Actual material properties were used to develop the effective strip method. 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.

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

where:

C_{ϕ} = Calibration coefficient (1.52 for LRFD);

M_m = Mean value of material factor (1.0);

F_m = Mean value of fabrication factor (1.0);

P_m = Mean value of professional factor (1.005);

e = Natural logarithmic base (2.718);

β = Target reliability index (2.5);

V_M = Coefficient of variation of material factor (0.1);

V_F = Coefficient of variation of fabrication factor (0.05);

C_p = Correction factor (1.022);

V_P = Coefficient of variation of test results (0.121);

V_Q = Coefficient of variation of load factor (0.21 for LRFD).

The values of M_m, V_M, F_m, and V_F were taken from Table F1 in AISI S100 (2007).

The AISI S213 (2007) adopts a LRFD resistance factor of 0.65 for wind load design and 0.60 for seismic design. The resistant factor for the proposed design method is 0.78. 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.

4. 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 developed design equations provide designers an analytical tool to calculate the nominal strength of CFS-SSSWs without conducting full-scale shear wall tests.

Acknowledgments

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