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SHEAR WALLS WITH COLD-FORMED STEEL FRAMING AND WOOD STRUCTURAL PANEL SHEATHING

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ABSTRACT

The construction of light gauge cold-formed steel framed shear walls with wood structural panel sheathing is gaining in popularity due to the ease and speed of construction, high shear capacity and efficient choices. However, the design of these walls is limited to what is available through research testing. There is currently no generally accepted design method that uses principles of mechanics to calculate the shear strength of cold-formed steel framed shear walls.

In this paper, an overview discussion regarding the development of a semi-analytical model is provided. This method is used to determine the shear strength of shear walls that are constructed with structural wood panel sheathing attached to cold-formed steel members with power-actuated fasteners.

This method was developed through a full-scale research test program including seismic testing of pre-constructed shear walls, and lateral connection tests of fasteners used for attachment of structural wood panels to light-gauge cold-formed steel framing members. Parameters affecting the shear performance of shear walls are discussed including the spacing and thickness of framing members, wood panel type and size, fastener type and spacing. The paper discusses the use of the analytical approach with other means of connections including building code-defined (IBC®) screws and power-actuated fasteners.

Keywords: Plywood, Seismic, Shear Wall, Cold-Formed Steel, Power-Actuated Fasteners

INTRODUCTION

The typical cold-formed steel (CFS) framed shear wall consists of evenly spaced steel studs for framing, steel tracks at the top and bottom of the walls, hold-down anchors at the end of the walls, and wood structural panel sheathing attached to cold-formed steel framing with a building code compliant or recognized fastener. A typical wall construction is shown in Figure 1. The wood structural panel may be required to be covered with a building code approved or recognized paper or a weather resistive barrier to provide corrosion resistance. A typical shear wall assembly is shown in Figure 2.

Design guidelines for shear walls constructed with cold-formed steel framing and wood structural panel sheathing are available in AISI S213-07, also known as AISI-Lateral, for some common shear wall configurations. However, AISI Lateral does not capture all possible shear wall configurations, nor does it provide guidance for variances in the shear wall construction. The 2009 International Building Code (IBC®) also does not address the use of proprietary fastening systems that can be used to attach wood structural panels to CFS framing members. There is no widely known analytical method of calculating the lateral performance of CFS framed shear walls with wood structural panel sheathing. Both AISI-Lateral and the 2009 IBC® allow the development of a design method based on testing and the principles of mechanics by using the strength and stiffness of the fastener connections.

The purpose of this paper is to describe the development of a semi-analytical model that is based on test data and mathematical calculations for the design of various shear wall assembly combinations with a proprietary power-actuated fastening system. Power-actuated fasteners have been used for attaching wood structural panels to cold-formed steel elements since 1986 (Nolan, 1998). Typical power-actuated fasteners have knurled shanks with diameters ranging from 0.100 inch (2.54 mm) to 0.120 inch (3.05 mm), shank length ranging from 1-1/2 inch (37 mm) to 2-1/2 inch (62 mm) and 1/4 inch (6 mm) head diameter, although these features may vary for different manufacturers. Power-actuated fasteners develop their holding mechanism through friction, generated between the fasteners and base steel during installation, keying, mechanical interlock with knurling of the shank of the fastener, and micro-brazing, zinc coating on the fastener is consumed due to the heat generated during the driving process in the base material to create a bond (Beck & Reuter, 2005). A typical power-actuated fastener is shown in Figure 3.

Figure 1. Typical wall construction with cold-formed steel framing and wood panel sheathing

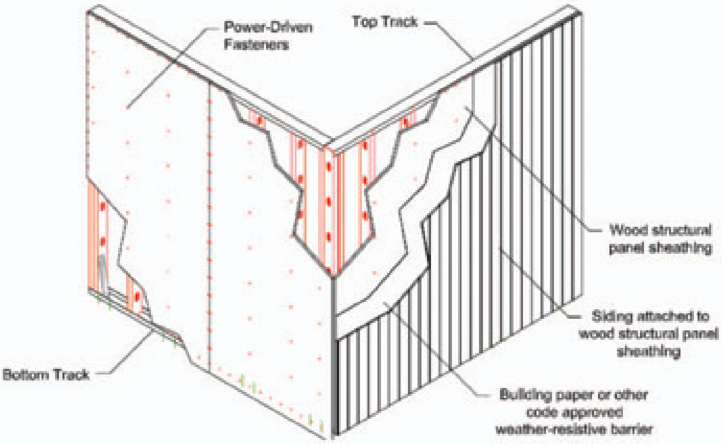

Figure 2. Typical shear wall frame with power-actuated fasteners

Figure 3. Typical power-actuated fastener for attachment of wood panels to cold-formed steel elements

The American Plywood Association (APA) provides a mathematical design guide for shear walls constructed with structural wood framing and wood panel sheathing based on the lateral (shear) capacity of building code prescribed nails (APA-154). However, this design guide and the other analytical models which are available as technical papers do not capture the unique performance characteristics of proprietary fastening systems. Proprietary power-actuated fastening systems generally provide improved load capacity, and quicker installation than building code (IBC®) defined attachment methods such as screws in addition to clean fastenings, and easy inspection advantages.

SMALL ELEMENT SHEAR TEST PROGRAM FOR POWER-ACTUATED FASTENERS

The first step in development of a semi-analytical model was to confirm the static shear load performance of the proprietary power-actuated fasteners when installed into cold-formed steel members through wood structural panels test pads. The tests were performed in accordance with ASTM D 1761-88(2000), *Standard Test Methods for Mechanical Fasteners in Wood* and ASTM E 1190-95 (2007), *Standard Test Methods for Strength of Power-Actuated Fasteners Installed in Structural Members*.

The single fastener static lateral load resistance (shear) tests were performed by attaching 12 in. (305 mm) long by 2 in. (50 mm) wide piece of structural plywood to a 12 in. (305 mm) long by 2 in. (50 mm) wide coupon cut from the light gauge cold-formed steel elements. The plywood and sheet steel coupons were configured with a lap-joint of 4 in. (100 mm). A single fastener was installed at the center line of the lap joint. Figure 4 shows the test configuration for the lateral load tests.

Figure 4. Lateral load test configuration

Table 1 shows the test scope and the sample size for the single fastener connection tests for lateral loads. The tests were conducted, progressing towards thicker structural panel wood members and thicker cold-formed steel base materials until a consistent failure mode of fastener pull-out from the cold-formed steel framing was achieved. The required numbers of test series was determined in accordance with Table 1 of ASTM D 2915-03, *Standard Practice for Evaluating Allowable Properties for Grades of Structural Lumber*, with a minimum of 15 tests. Additional tests were carried out until the resulting data complied with Table-1 of ASTM D 2915-03.

Table 1. Test Scope for Lateral Resistance of Power-Actuated Fasteners

Nominal Wood Structural Panel Thickness, inch (mm)	Minimum Thickness of Cold-Formed Steel Framing, gauge (mm)				
	22 (0.719)	20 (0.879)	18 (1.146)	16 (1.438)	14 (1.811)
3/8 (9.5)	15	15	15	15	15
15/32 (12)	15	15	15	15	15
19/32 (15)	15	15	15	15	15

FULL SCALE SHEAR WALL TESTS

A total of 12 full scale shear wall configurations were tested at Specialized Testing, Inc., an International Accreditation Service (IAS) certified third party test laboratory located in Santa Fe Springs, California. The tests parameters were chosen to capture a wide variety of common shear wall configurations by selecting the boundary conditions and representative shear walls that would reflect the actual field conditions. Table 2 shows the test matrix for the full-scale shear wall test program.

The tests were performed in accordance with ASTM E 2126-07a (2007), starting with a monotonic test protocol to develop reference parameters and followed by two CUREE (Consortium of Universities for Research in Earthquake Engineering) cyclic load tests. The CUREE test was repeated if the results of the first two tests were not within 10% of each other, as required by International Code Council Evaluation Services (ICC-ES), Acceptance Criteria for Power-Driven Pins for Shear Wall Assemblies with Cold-Formed Steel Framing and Wood Structural Panels (AC230), October 2008. ICC-ES is an independent evaluation agency which evaluates building products for compliance with the International Building Code. The average of the three tests was then used as the ultimate shear wall capacity. A total of 39 tests were performed.

Table 2. Test Scope for Full-Scale Shear Wall Tests

Cold-Formed Steel Thickness, gauge (mm)	Wood Structural Panel Thickness, inch (mm)	Frame Spacing, inch (mm) on center	Fastener Spacing, inch (mm)	
			6 (152)	2 (50)
20 (0.879)	3/8 (9.5)	24 (610)	3	3
	15/32 (12)	16 (406)	4	3
18 (1.146)	3/8 (9.5)	24 (610)	4	3
	19/32 (15)	16 (406)	4	3
16 (1.438)	15/32 (12)	24 (610)	3	3
	23/32 (18.3)	16 (406)	3	3
Total Tests			**39**	

The test walls were built as 8 ft (2438 mm) long by 8 ft (2438 mm) wide assemblies in accordance with ICC-ES AC230. The aspect ratio of 1:1 for tested shear wall assemblies helped determine the available shear strength of the walls with an aspect ratio equal to 2:1 or less (Brenston et al, 2006, ICC-ES AC230). The walls were composed of light-gauge, cold-formed steel C-studs with minimum flange width of 1-5/8 inches (41.3 mm), a minimum web depth of 3-1/2 inches (89 mm) and a minimum edge stiffener length of 3/8 inches (9.5 mm). The studs were spaced 16 inches (406 mm) or 24 inches (610 mm) on center. The steel tracks had a flange width of 1-1/4 inches (31.8 mm), with the same web depth as studs and were located at the top and bottom of the wall test specimens. The stud and track sections were fabricated from steel conforming to ASTM A 1003-05 standard to the designated thickness with a minimum yield strength of 33 ksi (227.5 MPa) for 20 and 18 gauge and 50 ksi (344.7 MPa) for 16 gauge sections. The steel sections are the most common shapes used in the construction of light-gauge steel framed wood structural panel sheathed shear wall assemblies. Structural 1 plywood was installed on each side of each test wall assembly with the Hilti X-GPN 37 MX proprietary power-actuated fasteners. These fasteners were placed at a distance of 3/8 inch (9.5 mm) from the edge of each plywood panel using Hilti GX-120 gas-actuated tool. The spacing of the fasteners around the wall perimeter was 2 or 6 inches (51 or 152 mm) on center. Fastener spacing in the field was 12 inches (305 mm) on center. The fastener installation was done in accordance with the manufacturer's installation instructions to eliminate underdriven and overdriven fasteners. Improperly attached fasteners can reduce the strength, stiffness and ductility of the shear wall assemblies and may result in wood panels not attaching to cold-formed steel framing or significant damage on the wood panels. Four 5/8 inch (16 mm) sill anchors (ASTM A307-07b Hex Bolts) and two hold-down connectors were used to attach the shear wall test specimens to the test frame. The hold-down connector rods were 7/8 inch (22 mm) diameter ASTM A 193-07 Grade B7 threaded rods which are attached to steel studs with 33 each No. 10-16x1-1/4" HWH #3 self-drilling screws. The shear wall assembly was attached to the test frame with a load cap on the top of the wall (Figure 5). The load cap member was an aluminum W8x13 member with a total weight of 133 lbs (592 N). The end tracks composed of back-to-back C studs were put in place to prevent failure of the end studs due to compression forces developed by lateral loads. A typical failure of plywood pull-over is shown in Figure 6.

Figure 5. Shear wall test set-up

Figure 6. Plywood pull-over failure for full-scale CUREE tests

CONCEPTS FOR DEVELOPMENT OF AN ANALYTICAL MODEL

The mechanical model represented in Figure 7 is a linear approach developed for structural wood framed, wood structural panel sheathed shear walls in American Plywood Association Research Report 154 (Tissell, 1993). The resulting shear resistance is calculated as the sum of individual fastener resistance as shown in Equation 1.

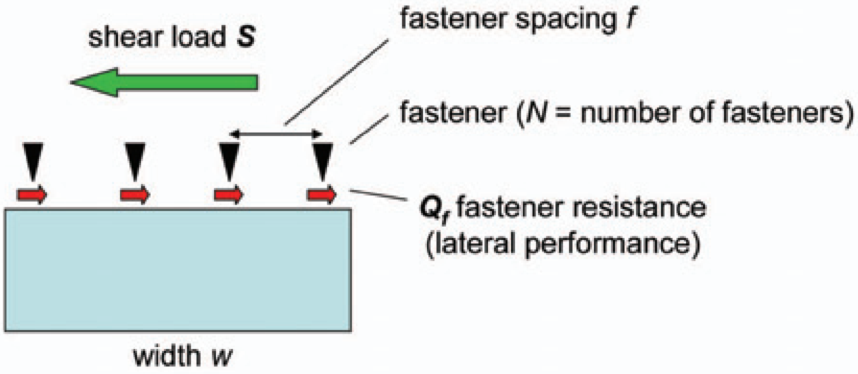

Figure 7. Analytical model for power-actuated fasteners

$$S_{nom} = N \cdot Q_f, \quad N = w / f \tag{1}$$

In this equation, Q_f is defined as the individual fastener shear strength and N is the number of fasteners in a given width (w; width: f; fastener spacing along the wall perimeter). The other factors taken into consideration are the frame spacing, type of wood panel, type and thickness of the base material and the type of attachment.

Equation 1 alone does not predict the actual behavior of the shear wall diaphragm system as the fasteners, sheathing material and cold-formed steel framing members act as a structural system. An evaluation concept based on statistics was introduced to correlate Equation 1 with the actual test results obtained from the full scale shear wall test program. A linear fitting function shown in Equation 2 was introduced to align the individual fastener performance with the actual shear wall test data.

$$f(N)=\alpha \cdot N + \beta + \gamma \cdot 1/s \tag{2}$$

where N is the number of fasteners per unit length and s is the stud spacing. Therefore, the predictive function S_{pre} was calculated by multiplying the nominal shear S_{nom} with the fitting function $f(N)$:

$$S_{pre} = (\alpha \cdot N + \beta + \gamma \cdot 1/s) \cdot S_{nom} \tag{3}$$

The parameters α, β and γ were calculated using a least squares curve fitting for the respective test data. After determination of the free parameters, α, β and γ, the coefficient of correlation between the shear wall test data, S_{actual} and the calculated shear wall strength S_{pre} was checked in accordance with ICC-ES AC230, Section 4.3.5. The coefficient of correlation must be greater than or equal to 0.85, for the fitting function to be considered as providing a sufficient degree of accuracy with respect to mathematical modelling.

In addition, the predictive data was further limited to have no calculated shear capacity higher than what was obtained in the actual test results to be conservative. Therefore, another adjustment factor was introduced for the configurations where the calculated capacity exceeded the tested capacity.

ANALYSIS OF SINGLE FASTENER SHEAR CONNECTION TESTS

The analysis of the test results for small element single fastener shear connection tests were conducted in accordance with AISI S100-2007, *North American Specification for the Design of Cold Formed Steel Structural Members*. The results were then adjusted to reflect the specified cold-formed steel tensile strength and the specified thickness by multiplying the test results with an adjustment factor, R_s, the ratios of specified tensile strength, $F_{u(specified)}$, to tested tensile strength, $F_{u(tested)}$; and specified base steel thickness, $t_{specified}$, to tested base steel thickness, t_{tested}, using the following formula:

$$R_s = \frac{F_{u(specified)}}{F_{u(testeed)}} \times \frac{t_{specified}}{t_{tested}} \tag{4}$$

Based on the results of the single fastener shear tests, a linear regression function was applied to the final test results after the base steel strength and thickness adjustments. Plywood thicknesses greater than 19/32 inch (15 mm) showed similar behavior to 19/32 inch (15 mm) plywood as the fasteners pulled out of the base steel at similar load levels.

Linear regression of the single fastener shear connection tests resulted in the following predictive equations for the strength, Q_f, of fastener connections in various plywood attachments to different cold-formed steel thicknesses:

- 3/8 inch plywood : $Q_{f,3/8} = 7716.14\,t - 4.00$ (5)
- 15/32 inch plywood : $Q_{f,15/32} = 9718.41\,t - 67.32$ (6)
- 19/32 inch plywood : $Q_{f,19/32} = 9776.87\,t - 53.98$ (7)

ANALYSIS OF FULL SCALE TEST RESULTS

The first-cycle envelope curve, also called backbone curve, is constructed for the positive and negative sides of the load versus deflection graph developed from CUREE tests. The first-cycle envelope curve is representative of the boundary load values and deflections for the first load cycles in the cyclic-shear wall test protocol plotted by linearly connecting the peak loads and deflections in each cycle as shown in Figure 8. The Load and Resistance Factor Design, (LRFD) nominal shear wall capacity is calculated based on strength and deflection (drift) limits. The nominal load is taken as either the average peak load from the first cycle envelope curve or determined from drift limitations. The wind drift limit is a maximum deflection of h/180, with h as the height of the test wall specimen. The seismic drift is determined in accordance with ASCE/SEI 7-2005, *Minimum Design Loads for Buildings and Other Structures,* Section 12.8.6 with the following equation;

$$\delta_{xe} = (\delta_x * I)/C_d \tag{8}$$

where

δ_x = The maximum inelastic response displacement taken as the lesser of code specified allowable story drift and the displacement at the peak load level from tests

δ_{xe} = Design level response displacement (in.)

I = Importance factor determined in accordance with Section 11.5.1 of ASCE/SEI 7

C_d = Deflection amplification factor, AISI S213-07

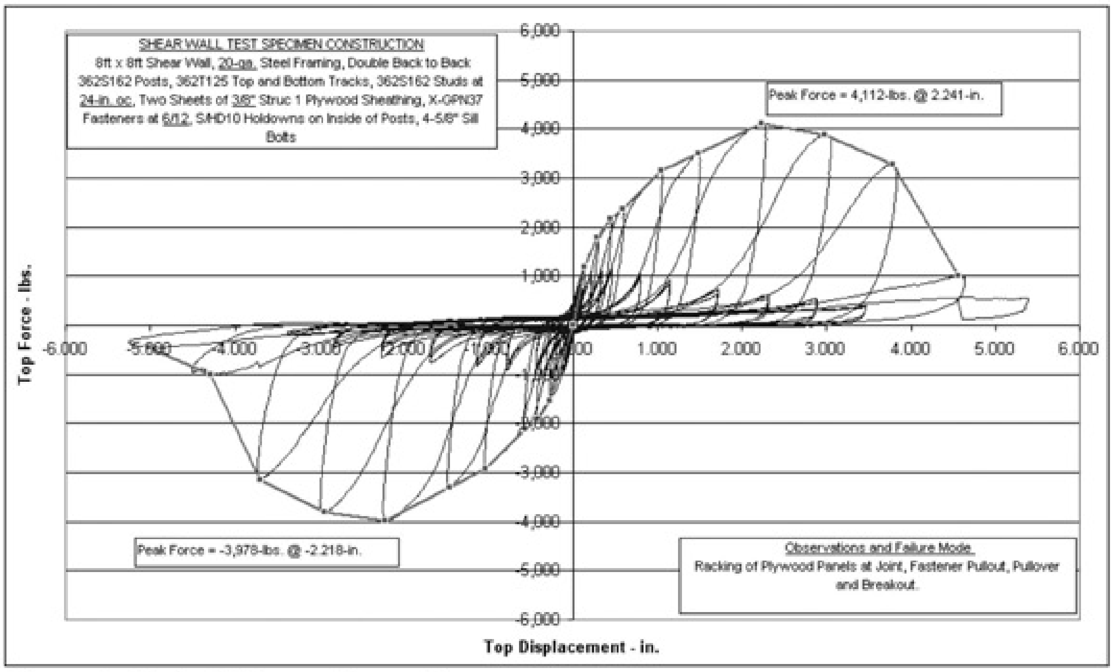

Figure 8. Typical first cycle envelope curve

The resulting nominal loads of the full-scale tests are presented in Table 3. The load results for the intermediate fastener spacings were calculated via linear interpolation as described in Section 4.2.1 of ICC-ES AC230.

Table 3. Nominal Loads, plf (kN/m) for Shear Wall Configurations with Various Fastener Spacing

Cold-Formed Steel Thickness, gauge (mm)	Wood Structural Panel Thickness, inch (mm)	Frame Spacing, inch (mm) on center	Fastener Spacing, inch (mm)			
			6 (152)	4 (102)	3 (76)	2 (50)
20 (0.879)	3/8 (9.5)	24 (610)	440 (6.4)	746 (10.9)	900 (13.1)	1053 (15.4)
	15/32 (12)	16 (406)	512 (7.5)	869 (12.7)	1048 (15.3)	1226 (17.9)
18 (1.146)	3/8 (9.5)	24 (610)	518 (7.6)	832 (12.1)	968 (14.1)	1145 (16.7)
	19/32 (15)	16 (406)	730 (10.6)	1203 (17.6)	1440 (21.0)	1676 (24.4)
16 (1.438)	15/32 (12)	24 (610)	844 (12.3)	1351 (19.7)	1604 (23.4)	1857 (27.1)
	23/32 (18.3)	16 (406)	1060 (15.5)	1724 (25.2)	2056 (30.0)	2389 (34.9)

LEAST SQUARES FITTING AND CALCULATION OF PARAMETERS

The adjusted shear strength of the fasteners and the known parameters allowed the use of a statistical function, LINEST. LINEST function helps to solve the following equation by using the least squares method to best fit the test data:

$$y = m_1 \cdot x_1 + m_2 \cdot x_2 + m_3 \cdot x_3 \tag{9}$$

In this equation, the target values, y, are the nominal loads from the full-scale test program and fitting parameters $m_1 = \gamma$, $m_2 = \beta$ and $m_3 = \alpha$ in Equation 2. In this statistical equation, all y and x values are known since they can be calculated based on the available test data. Thus, the LINEST function was employed through Microsoft® Excel to solve for the unknown parameters. A load reduction factor was determined based on the test values and the linear regression model values to ensure the predicted shear load values did not exceed the tested wall shear load capacity. The LINEST function helped determine the first part of Equation 3. Equation 3 can be re-written as:

$$S_{pre} = f(N) \cdot N \cdot Q_f \tag{10}$$

where

$$f(N) = (\alpha \cdot N + \beta + \gamma \cdot 1/s) \tag{11}$$

N is the number of fasteners along the edge of the shear wall assembly and was calculated by dividing the width of the shear wall test specimen by the fastener spacing. The comparison of the test results and the predicted load data based on the linear regression model is presented in Figure 9. The correlation between the test data and the predicted data was within the 10% of each other showing a strong correlation.

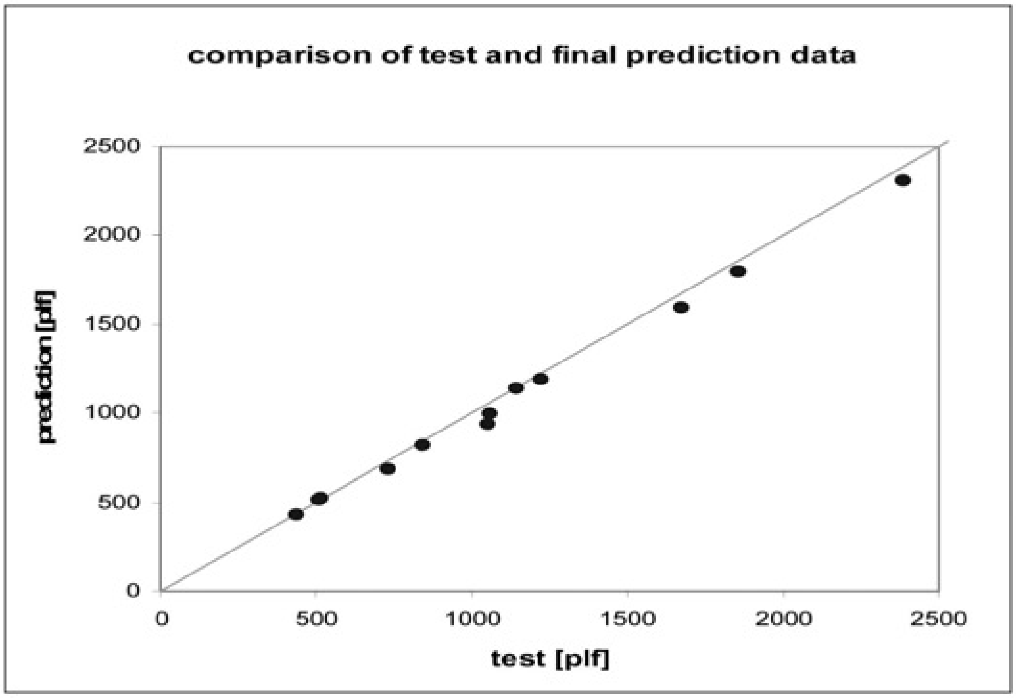

Figure 9. Comparison of predicted load data versus test data

The resulting design equation, based on comprehensive testing, AISI S213-07 (AISI-Lateral), APA-154 and utilizing statistical functions can be used to calculate the shear capacity shear wall configurations within the tested boundaries with the tested proprietary fastening system. This statistical model is an innovative method of calculating shear wall capacity. Based on the testing to date, it is also a conservative approach to analysis of full-scale shear wall test data, as no predictive load exceeds the test data. This data evaluation might provide a means for similar evaluations. The predicted data heavily depends on the test results for proprietary fasteners, therefore depending on the type of fastening system used, different results might be obtained.

CONCLUSION

Shear wall assemblies with cold-formed steel framing and wood structural panel sheathing are gaining more popularity due to ease of construction, economical advantage, speed and high lateral load capacity for resisting wind and seismic forces. The design of such shear walls can be made through AISI S213-07, which only lists a limited number of shear wall configurations or the published results from fastener manufacturers which are solely based on empirical results. Full-scale shear wall assembly testing provides a more accurate representation of the shear wall performance in an actual building than small element connection tests alone. However, the full-scale assembly tests also are also more expensive and time consuming. Since there is no industry wide accepted design guide for the design of shear walls an alternative model of semi-analytical design method has been developed based on testing of a significant number of full-scale shear wall assemblies and also testing the shear load performance of individual fasteners when used in connections of plywood to cold-formed steel members. Statistical methods have been used to understand the behavior of cold-formed steel framed shear wall assemblies and the shear strength of individual fasteners in the development of a semi-analytical design model for proprietary power-actuated fasteners. Additional adjustment factors were developed to ensure that calculated shear capacities did not exceed tested shear capacities. The results of the analysis shows a strong correlation between the predictive model based on single fastener testing, with results obtained from actual full-scale testing, supporting consideration of using predictive modeling in the design of shear wall assemblies.

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