Evaluation of Cold-formed Steel Connections Attached with Pneumatically Driven Pins

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ABSTRACT

A comprehensive experimental study was conducted to examine the shear and tensile strength of pneumatically driven pin connections used in cold-formed steel construction. This study included the key parameters that influence the connection strength: steel thickness (16-, 18- and 20-gauge steel), sheathing thickness (1/2" Unipan and 1/2" Dens-Glass Gold). The shear design values given in the AISI design specifications for screw connections are compared with those obtained from a series of lap shear tests and a good agreement is obtained. Initial analysis of the AISI design equation for tensile failure due to pull-over yielded poor results when compared to the withdrawal test values. Upon further analysis it was determined the connection failed in punch shear mode and the results compared well with the ACI punch shear analysis. The new equation developed in this study can be used to predict the strength of pneumatically driven pin connections in cold-formed steel construction.

INTRODUCTION

The use of cold-formed steel members in building construction began around the 1850's at the advent of the Industrial Revolution in Great Britain and the United States. However the industry only began widely using it in the 1940's. In 1946, the wide use of cold-formed steel in the construction industry in the United States led to the development of the Specification for the Design of Cold-Formed Steel Structural Members of the American Iron and Steel Institute (AISI). Subsequent additions incorporated investigation results that have improved the completeness and the surety of the specifications.

AISI's Cold-Formed Steel Design Specification (1996)[1,2], currently contain provisions for determining the strength of various limit states of connections using screws. Several manufacturers have been developing new types of fastening systems for cold-formed steel construction utilizing a pneumatically driven pin connection. Such a fastening system would meet the need to reduce time of construction, reduce the number of workers required to perform such construction and reduce the overall cost of the finished product. However the current AISI specification does allow testing, but does not stipulate how it should be carried out.

This study was conducted with the intention of developing formulae for pneumatically driven pin connections in cold formed steel.

EVALUATION OF CURRENT AVAILABLE DESIGN RECOMMENDATIONS FOR PNEUMATICALLY DRIVEN PINS

The nominal shear strength for screw connections is determined by the following (AISI, 1996)[1]

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$$P_{ns} := 4.2\cdot\sqrt{t_2^{\,3}\cdot d}\cdot F_{u2} \qquad \text{Tilting} \qquad (1)$$

$$P_{ns} := 2.7\cdot t_1\cdot d\cdot F_{u1} \qquad \text{Bearing} \qquad (2)$$

$$P_{ns} := 2.7\cdot t_2\cdot d\cdot F_{u2} \qquad \text{Bearing} \qquad (3)$$

d	Screw diameter
F_{u1}	Tensile strength of the member in contact with the screw head
F_{u2}	Tensile strength of the member not in contact with the screw head
t_1	Thickness of the member in contact with the screw head
t_2	Thickness of the member not in contact with the screw head

The nominal tensile strength of the screw connection is determined by the following: (AISI, 1996)[1]

$$P_{not} := 0.85\cdot t_c\cdot d\cdot F_{u2} \qquad \text{Pull – Out} \qquad (4)$$

where t_c is the lessor of the depth of the penetration and the thickness t_2.

$$P_{nov} := 1.5\cdot t_1\cdot d_w\cdot F_{u1} \qquad \text{Pull – Over} \qquad (5)$$

where d_w is the larger of the screw head diameter or the washer diameter and shall be taken not larger than ½-in (12.7mm).

The minimum spacing for the screws is the same as specified for bolts. The minimum distance between bolt hole centers must be greater than 3 times the diameter of the bolt. Previous tests have shown that almost all exhibit end failure when the distance from the center of the screw to the edge is less than 3 times the diameter of the screw.

In a previous study (Intertek Testing Services, 1998)[3] wall panels, which were constructed using the pneumatic pin fastening system, were analyzed using American Society for Testing and Materials (ASTM) 330 Negative Load Test. The chamber tested a series of 4-foot (1.22-m) wide by 8-foot (2.44-m) high wall assemblies. The study considered various sheathing used (gypsum and Dens-Glass Gold, a sheathing panel made of a patented silicone-treated core), fasteners (pin and screw) and spacing (6-inch (15.24-cm) and 8-inch (30.48-cm) on center. In the majority of cases the failure occurred when the heads of the fasteners pulled through the sheathing known as "pull-over". The comparisons illustrate the nominal design strength proposed by AISI is based on steel not gypsum. The results yielded computed values about 1.5 times higher than the tested pull-over capacity and 2.0 times higher than the tested pull-out capacity.

In 1995, ICBO[4] in conjunction with APA issued allowable shear and withdrawal values based on a series of studies conducted. The predicted nominal strength by AISI is relatively equal to the ICBO recommendations (1995) while the nominal withdrawal strength predicted by AISI is about 3.25 times higher than the ICBO recommendations. (Table 2A and 2B) The comparisons illustrate the nominal design strength proposed by AISI is based on steel not plywood.

Sheathing nominal 5/8 inch	Steel Stud Gauge	Fastener		System Failure psf	Pull-Over $P_{nov\ AISI}$
		Name	Spacing inches o.c.		
Dens-Glass Gold	20	AGS-100-150	6	74.4	109.28
Dens-Glass Gold	18	AGS-100-150	8	62.4	81.96
gypsum	20	AGS-100-150	6	60.3	68.26
gypsum	18	AGS-100-150	8	51.5	51.2
gypsum	20	S-12	8	60.8	51.2

Note: 1psf = 47.88 Pa, 1in = 2.54cm

Table 1. Withdrawal Values for 18 and 20 Gauge Cold-Formed Steel Framing and 0.100-inch-diameter Pins (Intertek Testing Services, 1998)[3]

Panel	Thickness t_1	Framing Width	Unblocked Diaphragms - Fastener Spacing	Gauge	Thickness t_2	$F_{u1}{}^1$	F_{u2}	Nominal Shear Strength AISI, P_{ns}		
	(in.)	(in.)	Allowable (lbs./ft.)	Designation	(in.)	(ksi)	(ksi)	Tilting (lbs.)	Bearing (lbs.)	Bearings (lbs.)
Structural I	0.5	1.5	**180.0**	20	0.0355	1.65	45	399.8	**222.8**	431.3
	0.5	1.5	**230.0**	18	0.0428	1.65	45	529.2	**222.8**	520.0
	0.5	1.5	**230.0**	16	0.0553	2.00	65	1122.7	**270.0**	970.5

Note: 1psi = 6.895 kN/m^2, 1in = 2.54cm, 1lb.=0.454kg

Table 2A. Design Recommendations for Allowable Shear Values for Horizontal Diaphragms Using Cold-Formed Steel and 0.100-inch-diameter Pins (ICBO, 1995)[4]

Panel	Thickness, t_1	Framing Width	Withdrawal	Gauge	Thickness, t_2	$F_{u1}{}^1$	F_{u2}	pull-over	pull-out
	(in.)	(in.)	Allowable (lbs./fastener)	Designation	(in.)	(ksi)	(ksi)	P_{nov} (lbs./fastener)	P_{not} (lbs./fastener)
Structural I	0.5	1.5	35.0	20	0.0355	1.65	45	386.7	135.8
	0.5	1.5	65.0	18	0.0428	1.65	45	386.7	163.7
	0.5	1.5	90.0	16	0.0553	1.65	65	386.7	305.5

Note: 1psi = 6.895 kN/m^2, 1in = 2.54cm, 1lb.=0.454kg

Table 2B. Design Recommendations for Allowable Withdrawal Values Using Cold-Formed Steel Framing and 0.100-inch-diameter Pins (ICBO, 1995)[4]

EXPERIMENTAL INVESTIGATION

This study demonstrates the use of pneumatic driven pins and their properties as they are used to attach sheathing to light gauge steel channels. The study considered sheathing and thickness variables, specifically Dens Glass Gold and Unipan, and 16, 18, and 20 gauge steel thickness. Lap shear and withdrawal tests demonstrate the shear capacity and the failure mode of a single pin connection subject to shear and tensile loading, respectively. The static load tests were also conducted to evaluate the shear resistance of the overall framed assembly (racking load assembly). A minimum of three identical specimens per category was tested as required by the AISI Specifications.

The connectors used were 0.100-inch (2.54-mm) diameter pins and were pneumatically driven into the sheathing until the pin was securely fastened into the cold-formed steel channel with a minimum penetration 1/4-inch (6.35-mm) through the frame. The sheathing manufacturer specifies this in order that the pin does not penetrate the sheathing to the point of causing damage to the outer skin.

Dens-Glass Gold is a unique "paperless" sheathing panel made of a patented silicone-treated core, surfaced with inorganic glass mat facings and a "gold" alkali-resistant coating. Unlike its counterpart, Unipan is a lightweight concrete backerboard of cement with polymer and lightweight aggregate wrapped in a fiberglass mesh. The materials share durability qualities, in addition to similar moisture resistance, handling and installation ease.

	½" Dens-Glass Gold (Gypsum)	½" Unipan (Cement)
Compressive Strength (lbs./sq.in.)	0.500×10^3	1.305×10^3
Flexural Ultimate Strength (lbs./sq.in.)[5,6]	0.373×10^3	0.986×10^3

Note: 1psi = 6.895 kN/m^2

Table 3. Mechanical Properties of Cold-Formed Steel

A system of identification was developed to differentiate between the various types of specimens. For each test, a seven-digit code was assigned as illustrated in (Figure 1)

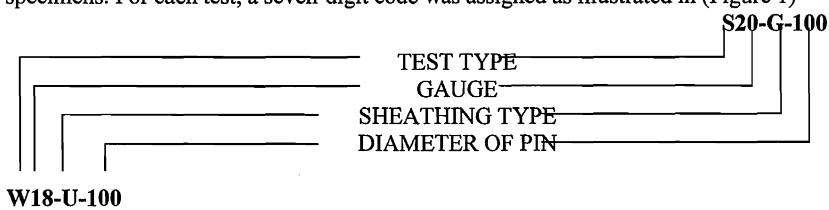

Figure 1. Specimen Nomenclature

The first digit signifies which of the three tests was being analyzed: S for shear and W for withdrawal. The next two digits signify the gauge of steel tested: 20-gauge, 18-gauge and 16-gauge. The following digit signifies which sheathing was used, either G for Dens-Glass Gold or U for Unipan. The last three digits signify the diameter of the pin being used, for example, 100 for 0.100-inches (2.54mm). In the example, S20-G-100 indicates a 20-gauge steel stud with Dens-Glass Gold subjected to a shear test using a 0.100-inch (2.54mm) diameter pin.

A series of shear tests (Figure 2), and withdrawal tests (Figure 3) were conducted for three different gauges of cold-formed steel (16, 18, and 20 gauge) and two types of sheathing (Unipan and Dens-Glass Gold). Tension coupon testing was not part of the scope of this experiment. Table 2[1,7] lists the mechanical properties of cold-formed steel.

Designation (mils)	Min. Thickness (in.)	Reference Gauge	Yield Strength (ksi.)	Min. Tensile Strength (ksi.)
33	0.0329	20	33	45
43	0.0428	18	33	45
54	0.0538	16	50	65

Note: 1psi = 6.895 kN/m^2, 1in = 2.54cm, 1lb.=0.454kg

Table 4. Mechanical Properties of Cold-Formed Steel[1,7]

EXPERIMENTAL PROCEDURE

1. Shear Test Specimens: The shear test specimens consisted of a cold-formed steel channel being attached on the flange side to the sheathing by a pin. The pin was only fastened to one side of the flange. The extended side of the channel was connected to a mounting bracket with bolts and nuts through the flange to permit the application of axial loads. The bottom side of the sheathing is attached to the base of the apparatus by steel angles upon which a reaction to the force was applied.(Figure 2) The specimens were designed with the intention of having the failure occur in the vicinity of the pin fastener. Load was applied parallel to the web, through the flanges, at a free running crosshead speed of 0.05-inches (1.27mm) per minute using an Instron Testing Machine. Each specimen was tested until failure. The data recorded during the test included the applied load and the relative joint displacement.
2. Withdrawal (Tension) Test: The withdrawal test assemblies incorporated the use of sheathing connected to cold-formed steel channels by steel pins. The pins were driven through the metal framing a minimum of ¼-inch and the pins were only fastened to one side of the flanges. The distance between fasteners was set at 8-inches (20.32cm) on center as recommended by the fasteners manufacturer (Figure 3). Load was applied parallel to the web, through the flanges, at a free running crosshead speed of 0.1-inches per minute by using the Instron Testing Machine. Each specimen was tested until failure. The applied load and the relative joint displacement data were recorded during the test.

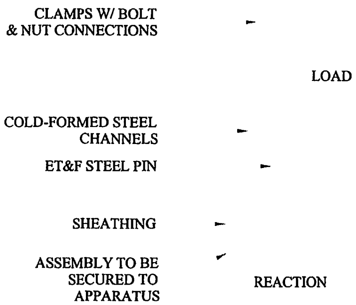

Figure 2. Lap Shear Test Setup

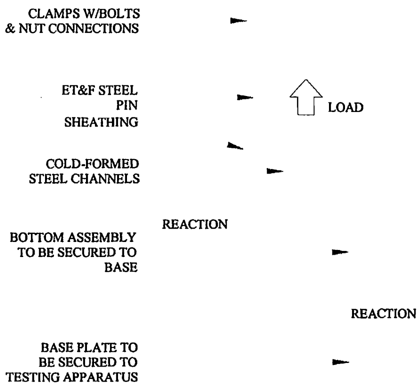

Figure 3. Withdrawal Test Setup

EVALUATION OF TEST DATA

SHEAR CAPACITY EVALUATION

The test results indicate some slippage of the frame during the tests. Figure 4 and 5 show the typical shear failures for Unipan and Dens-Glass Gold. The points shown use the average for three tests.

An overall summary of results for the lap shear test is provided in Table 5. In general the thicker gage steel framing yielded higher failure loads and Unipan yielded ultimate shear values somewhat higher then the Dens-Glass Gold.

The measured shear capacities are compared with the AISI nominal shear strength values in Table 6. The failure loads were not found to have any significant dependence on the gage size. On all cases the connections failed by the pin bearing on the sheathing, which was consistent with the failure mode predicted by AISI.

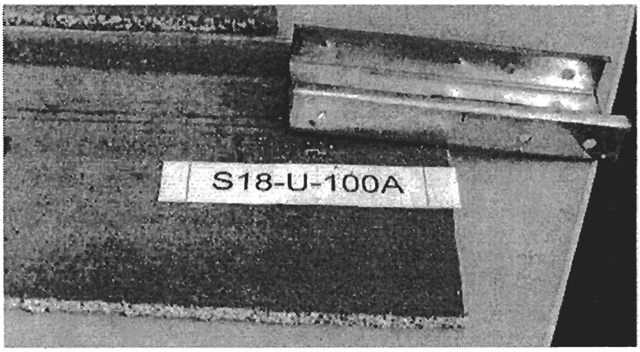

Figure 4. Typical Failure for Shear Assembly (Unipan)

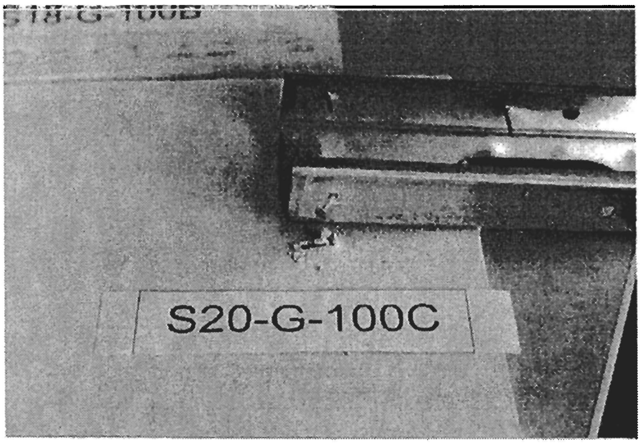

Figure 5. Typical Failure for Shear Assembly (Dens-Glass Gold)

	Failure Load (per pin)	Sheathing t_1	Flange t_2	Pin diameter	Tensile Fu_1	Tensile Fu_2
Specimen	lbs.	in.	in.	in.	ksi	ksi
S20-G-100	122.10	0.5	0.0329	0.100	0.373	45
S20-U-100	156.80	0.5	0.0329	0.100	0.986	45
S18-G-100	118.10	0.5	0.0428	0.100	0.373	45
S18-U-100	136.53	0.5	0.0428	0.100	0.986	45
S16-G-100	133.17	0.5	0.0538	0.100	0.373	65
S16-U-100	168.27	0.5	0.0538	0.100	0.986	65

Note: 1in. = 2.54cm, 1lb.=0.454kg, 1psi = 6.895 kN/m^2

Table 5. Overall Summary for Lap Shear Test

	Shear	Nominal Shear Strength Design			Ratio
Test #	Actual (kips)	ilting (kips)	Sheathing earing (kips)	Steel earing (kips)	Pu/Pns
S20-U-100	0.157	0.357	**0.133**	0.400	1.179
S18-U-100	0.137	0.491	**0.133**	0.495	1.026
S16-U-100	0.168	1.077	**0.133**	0.944	1.265
S20-G-100	0.122	0.357	**0.050**	0.400	2.442
S18-G-100	0.118	0.491	**0.050**	0.495	2.362
S16-G-100	0.133	1.077	**0.050**	0.944	2.664

Note: P_{ns} shall be taken as the smallest of the nominal shear strengths

Note: 1in. = 2.54cm, 1lb.=0.454kg, 1psi = 6.895 kN/m^2

Table 6. Measured vs. Predicted Shear Capacities of Pin Connections

WITHDRAWAL CAPACITY EVALUATION

The point for each combination of test variables is for an average of three tests. Figure 6 and 7 show the typical type of withdrawal failures for Unipan and Dens-Glass Gold. The measured withdrawal loads are compared with the AISI nominal withdrawal strength values in Table 7. The measured values ranged from 22.1% to 142.6% of the AISI strength. The withdrawal tests conducted by (Intertek Services, 1998)[3] yielded withdrawal strengths of about 68.1% to 118.8% of AISI values when using Dens-Glass Gold and gypsum sheathing.

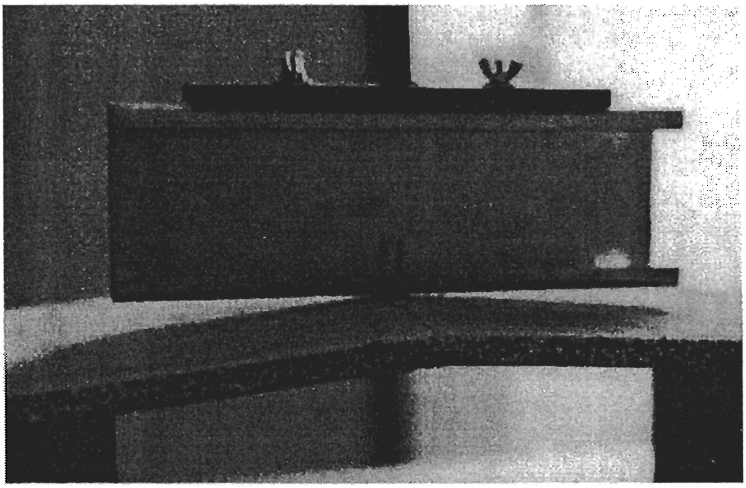

Figure 6. Withdrawal Assembly at Point of Failure (Unipan)

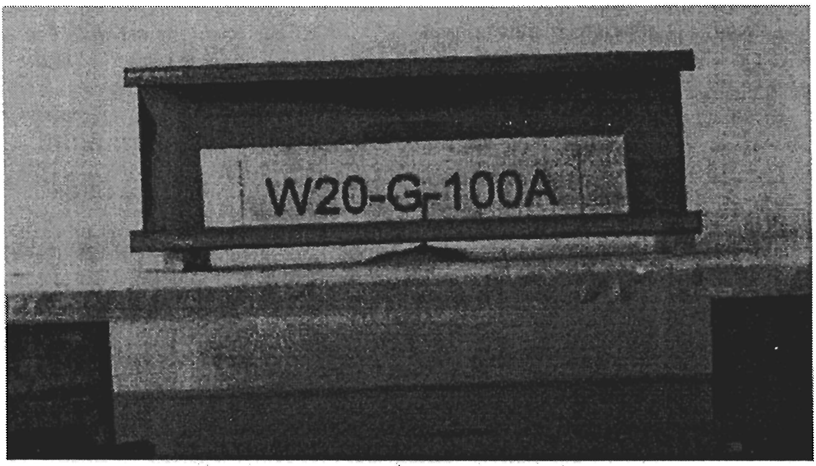

Figure 7. Withdrawal Failure (Dens-Glass Gold)

Test #	Measured Withdrawal Capacity	AISI Nominal Withdrawal Capacity P_n		Ratio
		Pull-Over	Pull-Out	P_u/P_n
	P_u (lbs)	P_{nov} (lbs)	P_{not} (lbs)	
W20-U-100	25.5	115.5	125.8	0.221
W18-U-100	42.4	115.5	163.3	0.367
W16-U-100	69.5	115.5	205.8	0.602
W20-G-100	33.3	43.7	125.8	0.762
W18-G-100	32.9	43.7	163.3	0.753
W16-G-100	62.3	43.7	205.8	1.426

Note: 1lb.=0.454kg

Table 7. Measured vs. Predicted Withdrawal Capacities of Pin Connections

PROPOSED MODIFICATION FOR NOMINAL TENSILE STRENGTH OF PIN CONNECTIONS

The AISI Design Specifications for screw connections were determined to be unconservative for calculating the shear capacity for Unipan with measured values ranging from 71.8% to 88.6% and to conservative for Dens-Glass Gold ranging from 164% to 185% in this study. The AISI Design Specification for withdrawal capacity of screw connections was found to over predict the capacity of the specimens tested.

During the analysis of the 'shear' and 'pull-over' failure, modeling assumptions made, received closer attention. The pull-over equation is a slight modification to a British equation which considered the diameter of the head in contact with the surface of the material. The variables used in determining the load capacity consider the following, the diameter of the head, the thickness of material for which the pin is being pulled through, and the tensile strength of the material itself. In reviewing Pekoz, (1990)[8] report of the pull-over equation, the equation was obtained using studies, which reflected materials with common characteristics. The resulting failures were ductile in nature allowing greater elasticity during loading. Thus, the AISI equations are intended for steel-to-steel connections, not gypsum or concrete sheathing.

In comparison the measured loads from the shear and withdrawal tests are conducted with materials having brittle qualities. In punching shear failure of brittle materials ACI Code (1995)[9] provides the following equation for nominal shear strength.

$$V_c := 4 \cdot \lambda \cdot \sqrt{f_c} \cdot b_o \cdot d \qquad (6)$$

Where b_o = perimeter of critical section for slabs at a distance of d/2 from the face of the column (in.)
d= depth of slab (in.)
λ= 0.75 for lightweight concrete
f'c= compressive strength

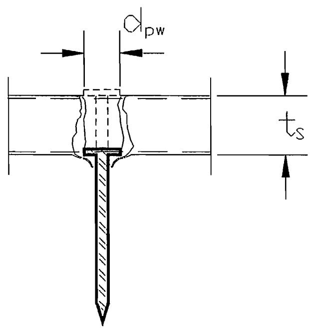

Figure 8. Pull-Over Failure

The withdrawal tests indicated that the pull-out occurred in the manner shown in Figure 8. Substituting b_o with d_{pw} (diameter of head of pin = $1.5\pi d_p$) and d with t_s ACI equation becomes

$$V_c := 4 \cdot \lambda \cdot \sqrt{f'_c} \cdot d_{pw} \cdot t_s \tag{7}$$

The pull-out strength was evaluated using the modified ACI equation and considered the lightweight concrete reduction factor. Due to the failure type pull-over of the sheathing it was determined that the steel gauges had minimal effect on the outcome of the results. Table 8 compares the modified ACI equation with the experimental values and the results are found to be in good agreement with Unipan but not with Dens-Glass Gold.

	Measured Withdrawal Capacity	Modified ACI P_n	Ratio
Test #	P_u (lbs)	P_n (lbs)	P_u/P_n
W20-U-100	25.5	39.9	0.639
W18-U-100	42.4	39.9	1.063
W16-U-100	69.5	39.9	1.742
W20-G-100	33.3	24.7	1.348
W18-G-100	32.9	24.7	1.332
W16-G-100	62.3	24.7	2.522

Note: 1lb.=0.454kg

Table 8. Comparison for Pull-Over Using ACI (modified)

CONCLUSIONS

A comprehensive study of the behavior of sheathing attached to cold-formed steel structures using pin connections has demonstrated the following:

-The shear strength of pin connections were in good agreement with the AISI Design Specification for nominal shear strength for screw connections.

-The AISI Design Specifications for nominal pull-over strength did not accurately predict the withdrawal test results.

-The thickness of the steel channel and the types of sheathing used did not effect the shear capacity of the section.

- The AISI equations are intended for steel-to-steel connections, not gypsum or concrete sheathing

-A new empirical equation for pull-over strengths using the punch shear analysis was developed based on the American Concrete Institute Specifications:

$$V_c := 4 \cdot \lambda \cdot \sqrt{f'_c} \cdot d_{pw} \cdot t_s \qquad (7)$$

Where d_{pw} = perimeter of critical section as defined from the head of the pin (in.)=1.5πd

t_s = thickness of sheathing (inches)

λ= 0.75 for lightweight concrete

f'c = compressive stress of material (psi)

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APPENDIX A.

	Experimenta l Shear Capacity	Design Nominal Shear Strength AISI			Ratio
Test #	Actual (kips)	Tilting (kips)	Bearing (kips)	Bearing (kips)	Pu/Pns
S20-U-100A	0.114	0.357	**0.133**	0.400	0.854
S20-U-100B	0.197	0.357	**0.133**	0.400	1.477
S20-U-100C	0.160	0.357	**0.133**	0.400	1.205
S18-U-100A	0.128	0.491	**0.133**	0.495	0.963
S18-U-100B	0.090	0.491	**0.133**	0.495	0.678
S18-U-100C	0.191	0.491	**0.133**	0.495	1.438
S16-U-100A	0.201	1.077	**0.133**	0.944	1.514
S16-U-100B	0.143	1.077	**0.133**	0.944	1.077
S16-U-100C	0.160	1.077	**0.133**	0.944	1.205
S20-G-100A	0.110	0.357	**0.050**	0.400	2.206
S20-G-100B	0.133	0.357	**0.050**	0.400	2.658
S20-G-100C	0.123	0.357	**0.050**	0.400	2.462
S18-G-100A	0.110	0.491	**0.050**	0.495	2.190
S18-G-100B	0.126	0.491	**0.050**	0.495	2.512
S18-G-100C	0.119	0.491	**0.050**	0.495	2.384
S16-G-100A	0.146	1.077	**0.050**	0.944	2.916
S16-G-100B	0.117	1.077	**0.050**	0.944	2.336
S16-G-100C	0.137	1.077	**0.050**	0.944	2.738

Mean for Unipan	1.157
Std.Dev. for Unipan	0.291
C.O.V.	25.18%
Mean for Dens-Glass Gold	2.489
Std. Dev. for Dens-Glass Gold	0.244
C.O.V.	9.82%
Mean for all tests	1.823
Std. Dev. for all tests	0.733
C.O.V.	40.23%

Table 9. Comparison of AISI Shear Values with Test Results

	Measured Withdrawal Load	Pull-Over	Ratio
Test #	Pu (kips)	Pnov (kips)	Pu/Pnov
W20-U-100A	0.0250	**0.115**	0.217
W20-U-100B	0.0354	**0.115**	0.308
W20-U-100C	0.0161	**0.115**	0.140
W18-U-100A	0.0322	**0.115**	0.280
W18-U-100B	0.0515	**0.115**	0.448
W18-U-100C	0.0435	**0.115**	0.378
W16-U-100A	0.0878	**0.115**	0.763
W16-U-100B	0.0660	**0.115**	0.574
W16-U-100C	0.0548	**0.115**	0.477
W20-G-100A	0.0263	**0.044**	0.598
W20-G-100B	0.0137	**0.044**	0.311
W20-G-100C	0.0600	**0.044**	1.364
W18-G-100A	0.0290	**0.044**	0.659
W18-G-100B	0.0387	**0.044**	0.880
W18-G-100C	0.0309	**0.044**	0.702
W16-G-100A	0.0830	**0.044**	1.886
W16-G-100B	0.0515	**0.044**	1.170
W16-G-100C	0.0523	**0.044**	1.189
	Mean for all tests		0.686
	Std. Dev. For all tests		0.461
	C.O.V.		67.23%
	Mean for Unipan		0.398
	Std.Dev. For Unipan		0.192
	C.O.V.		48.19%
	Mean for Dens-Glass Gold		0.973
	Std. Dev. For Dens-Glass Gold		0.478
	C.O.V.		49.16%

Table 10. Comparison of AISI Pull-Over Values with Test Results