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research report

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STRENGTH OF STEEL-TO-STEEL SCREW CONNECTIONS – UPDATE TO PROVISIONS

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Abstract

The objective of this project is to review the existing provisions of the AISI S100-16 *North American Specification for Cold-Formed Steel Structural Members*, for screw connections loaded in shear and tension (but not combined actions). A recent study by the Steel Deck Institute (Sputo 2017) revealed possible unconservative results for screw pull-over, particularly in thinner sheets and/or lower ductility.

This study performed a comprehensive analysis of available steel-to-steel screw connection strength test data, totaling 702 shear tests, 143 pull-over tests, and 335 pull-out tests. The tested strength of these connections was compared to the predicted strength from the existing strength equations in the AISI S100-16 Standard. The validity of the existing equations was evaluated based on how well the predicted strengths matched the tested strengths. From this analysis, recommended adjustments to the equations, factors of safety, and/or resistance were determined and reported.

This study found that the existing equations in AISI S100-16 for screw connections loaded in shear do not need to be revised, although the resistance factors for both LRFD and LSD could be increased.

For the limit state of pull-over, the existing equations in AISI S100-16 do not need to be revised, while the resistance and safety factors for pull-over could be revised, with distinction between connections with ductile steel and connections with low-ductility steel. This study did not look at the effect of geometry on pull-over, and further investigation is recommended.

For the limit state of pull-out, the analysis of available test data indicates that the current nominal strength prediction equation in AISI S100-16 should to be revised by including an adjustment factor into the equation. The proposed adjustment factor results in increased usable strength in connections with sheet thickness greater than 0.04 inches. It was found that the pull-out resistance factors could be increased slightly. It should be noted that a large majority of the pull-out tests analyzed consisted of connections with ductile steel; therefore additional research should be conducted before conclusions can be drawn regarding pull-out failure of low-ductility screw connections.

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C_p = Correction factor

C_φ = Calibration coefficient (AISI S100-16 Standard)

F_m = Mean value of fabrication factor

F_{u1} = Nominal tensile strength of member in contact with screw head or washer

F_{u2} = Nominal tensile strength of member not in contact with screw head or washer

M_m = Mean value of material factor

P_m = Mean value of professional factor

P_{not} = Nominal pull-out strength of sheet per screw

P_{nv} = Nominal shear strength of sheet per screw

V_F = Coefficient of variation of fabrication factor

V_M = Coefficient of variation of material factor

V_P = Coefficient of variation of test results, but not less than 0.065

V_Q = Coefficient of variation of load effect

d = Nominal screw diameter

d_h = Screw head diameter or hex washer head integral washer diameter

d'_w = Effective pull-over resistance diameter

m = Degrees of freedom

n = Total number of samples included in the specific analysis

t_1 = Thickness of member in contact with screw head or washer

t_2 = Thickness of member not in contact with screw head or washer

t_c = Thickness of sheet not in contact with screw head or washer

t_w = Steel washer thickness

βo = Target reliability index

Φ = Phi, resistance factor calculated separately for use in either LRFD or LSD

Ω = Omega, factor of safety calculated for use in ASD

Chapter 1 - Introduction

Cold-formed steel structures often rely on steel-to-steel screw connections for strength and convenience of installation. As screw installation techniques and technologies advance, steel screw connections are becoming more economical and therefore more important in the structural engineering and construction industries. As such, it is important to confirm that current provisions are accurate and appropriate.

The AISI S100 North American Specification for Cold-Formed Steel Structural Members provisions for steel-to-steel screw connections loaded in shear and tension (but not combined actions) are being reviewed. The resistance factor and factor of safety have not been reviewed since these provisions were initially added to the Standard in 1990. This project seeks to take a fresh look at the currently available database of testing to determine what changes, if any, are needed to these provisions.

The existing provisions for screw connections in the American Iron and Steel Institute (AISI) S100-16 Standard are based on European testing on steels and fasteners which may not reflect those found in the North American market (Pekoz, 1990). Since the implementation of these provisions, several new studies have tested the strength of steel-to-steel screw connections. Specifically, a recent unfunded study by the Steel Deck Institute (Sputo, 2017) presented potential unconservative predictions, specifically for screw pull-over for thinner sheets and/or lower ductility steels. A 1996 study by Kreiner also found possible unconservative pull-over results. This study aims to review the current screw provisions in the S100, with the potential of revising existing strength equations, resistance factors, and factors of safety. The failure modes analyzed in this study are shear (tilting and bearing), pull-out, and pull-over. Failure of the screw itself is not considered in this study and tests that failed in this limit state were excluded from the database. Combined shear and tension loading was likewise not considered in this study.

In accordance with the AISI S100-16 Standard, the current Load and Resistance Factor Design (LRFD) resistance factor is 0.50, the factor of safety for Allowable Strength Design (ASD) is 3.00, and the Limit States Design (LSD) resistance factor is 0.40. These apply to all limit states.

Phase 1 of this study examines steel-to-steel screw connections in shear, with a data set of 702 strength tests from 9 different reports. The observed strength from these tests is compared to the calculated strength according to the AISI S100 to determine the viability of the current provisions.

Phase 2 of this study examines steel-to-steel screw connections in tension. Screw connections subject to tensile forces can fail in two ways: the material pulling over the screw head and washer (pull-over), the screw pulling out from the plate (pull-out). This study includes the results for 143 connections which failed by pullover and 335 connections which failed by pullout.

This study limited itself to tests which follow the AISI S905 test protocol as far as specimen configuration. Some tests (Sivapathasundaram and Mahendran) were similar enough to the S905 protocol that they were included in the database.

Within this report, the ductility of the steel is considered for some limit states. For the purpose of this report, “ductile” steel is considered to be a steel that complies with AISI S100-16, Section A3.1.1, with a minimum elongation of 10% or greater. “Low-ductility” steel is considered to be a steel that complies with AISI S100-16, Section A3.1.2, with a minimum elongation of 3% or greater., but less than 10%, or a steel that complies with Section A3.1.3, with a minimum elongation of less than 3% .

Chapter 2 – Screws Loaded in Shear

Section 2.1 - Introduction

Phase 1 of this study looked at the limit state of shear of the connection. The limit state of the screw shear was not included in this study, as it does not have an analytical solution in the AISI S100 Standard. This section of the study performed an analysis of existing test data from screw connections in shear to determine if the current shear strength equations, resistance factors, and factors of safety need to be revised. This study only examined test data from 2-ply steel-to-steel screw connection strength tests. Several potential factors that may affect connection strength were considered throughout this study, including: number of screws, sheet ductility, sheet thickness, and ratio of sheet thickness. The effects of end distance, screw spacing, and patterns of screw arrangement on connection strength were not considered in this study, as they were examined in-depth in Li, Ma, and Yao (2010). The reader is referred to that paper for additional information.

As currently contained in the AISI S100-16 Standard, the nominal shear strength of steel sheet per screw, P_{nv}, shall be determined by the following:

For $t_2/t_1 \leq 1.0$, P_{nv} shall be taken as the smallest of

$P_{nv} = 4.2(t_2^3 d)^{1/2} F_{u2}$ AISI S100-16 Eq. J4.3.1-1

$P_{nv} = 2.7 t_1 d F_{u1}$ AISI S100-16 Eq. J4.3.1-2

$P_{nv} = 2.7 t_2 d F_{u2}$ AISI S100-16 Eq. J4.3.1-3

For $t_2/t_1 \geq 2.5$, P_{nv} shall be taken as the smaller of

$P_{nv} = 2.7t_1dF_{u1}$ AISI S100-16 Eq. J4.3.1-4

$P_{nv} = 2.7t_2dF_{u2}$ AISI S100-16 Eq. J4.3.1-5

For $1.0 < t_2/t_1 < 2.5$, P_{nv} shall be calculated by linear interpolation between the above two cases.

Where:

d = Nominal screw diameter

P_{nv} = Nominal shear strength of sheet per screw

t_1 = Thickness of member in contact with screw head or washer

t_2 = Thickness of member not in contact with screw head or washer

F_{u1} = Nominal tensile strength of member in contact with screw head or washer

F_{u2} = Nominal tensile strength of member not in contact with screw head or washer

In performing this study, the following items were considered:

1. In accordance with AISI S100-16 Commentary Equation C-B3.2.2-16, the factor of safety, Ω, can be calculated based on the ratio of live loads to dead loads, which is assumed to equal to 5:1 in this Standard. For this case, Ω can be set equal to 1.5333 divided by Φ. For this report, this calculation will be labeled "Alternate calculation of Ω."

2. In accordance Section K2.1.1 of AISI S100-16 a reliability index of 3.5 was used for LRFD, and a reliability index of 4.0 was used for LSD.

3. Since it appears that AISI COS Ballot S18-455 will pass and be incorporated into AISI S100-20, the value of V_m was set to 0.08 (0.10 in S100-16) and V_f was set to 0.05 (0.10 in S100-16). This applies to shear bearing and tilting only and does not apply to screw pullover or pullout.

Section 2.2 - Previous Studies

In this section, each individual test report or paper is reported on individually.

Section 2.2.1 - Janusz, M., Sledz, M. and Moravek, S. (1979). "Teks Fasteners, Pullout and Shear Characteristics In Various Thicknesses of Steels, Second Edition." *Buildex Division-Illinois Tools Works, Inc.*

141 data points were collected from this report. All 141 tests consisted of single screw connections. All connections tested in this report consisted of ductile steel. A summary of this dataset is reported in Table 2-1.

Table 2-1 – Janusz, Sledz, and Moravek (1979)

	2016	**2020**
n:	141	141
m:	140	140
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.054	1.054
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.08
V_F:	0.1	0.05
C_p:	1.022	1.022
V_p:	0.227	0.227
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.054	1.054
Standard Deviation:	0.240	0.240
Coefficient of Variation:	0.227	0.227
Φ (LRFD):	0.533	0.564
Ω (ASD):	3.005	2.835
Alt Ω:	2.879	2.716
Φ (LSD):	0.419	0.448

<u>Section 2.2.2</u> - Pham, H. and Moen, C. (2015). "Stiffness and Strength of Single Shear Cold-Formed Steel Screw-Fastened Connections." *Structural Engineering and Materials*, 5-15.

15 data points were collected from this paper, however one of these tests failed in screw shear, and therefore that data point was omitted from this analysis for the purpose of this review. All tests in this report consisted of single screw connections with ductile steel. A summary of this dataset is reported in Table 2-2.

Table 2-2 – Pham and Moen (2015)

	2016	**2020**
n:	15	15
m:	14	14
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.039	1.039
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.08
V_F:	0.1	0.05
C_p:	1.244	1.244
V_p:	0.184	0.184
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.039	1.039
Standard Deviation:	0.191	0.191
Coefficient of Variation:	0.184	0.184
Φ (LRFD):	0.579	0.590
Ω (ASD):	2.765	2.710
Alt Ω:	2.648	2.597
Φ (LSD):	0.462	0.473

<u>Section 2.2.3</u> - Huynh, M., Pham, C., and Hancock, G. (2018). "Experiments on Screwed Connections in Shear Using High Strength Cold-Reduced Sheet Steels." *Eighth International Conference on Thin-Walled Structures*, 1-13.

11 data points were collected from this paper. This research focused on testing screw connections of cold-formed sheet steels of intermediate thickness, as the authors noted that there was previously very little data of these connections in shear. All tests in this report used double screw connections with low-ductility steel. A summary of this dataset is reported in Table 2-3.

Table 2-3 – Huynh, Pham, and Hancock (2018)

	2016	**2020**
n:	11	11
m:	10	10
C_{φ} (LRFD):	1.52	1.52
C_{φ} (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.015	1.015
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.080
V_F:	0.1	0.05
C_p:	1.364	1.364
V_p:	0.209	0.209
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.015	1.015
Standard Deviation:	0.212	0.212
Coefficient of Variation:	0.209	0.209
Φ (LRFD):	0.535	0.524
Ω (ASD):	2.991	3.052
Alt Ω:	2.866	2.925
Φ (LSD):	0.424	0.414

As shown below, when comparing the ratio of tested strength to calculated strength versus the ratio of bottom thickness to top thickness, there is a noticeable reduction in the ratio of P_{test}/P_{calc} in the t_2/t_1 range between 0.75 to 2.25. This will be discussed further in Section 2.4.2.

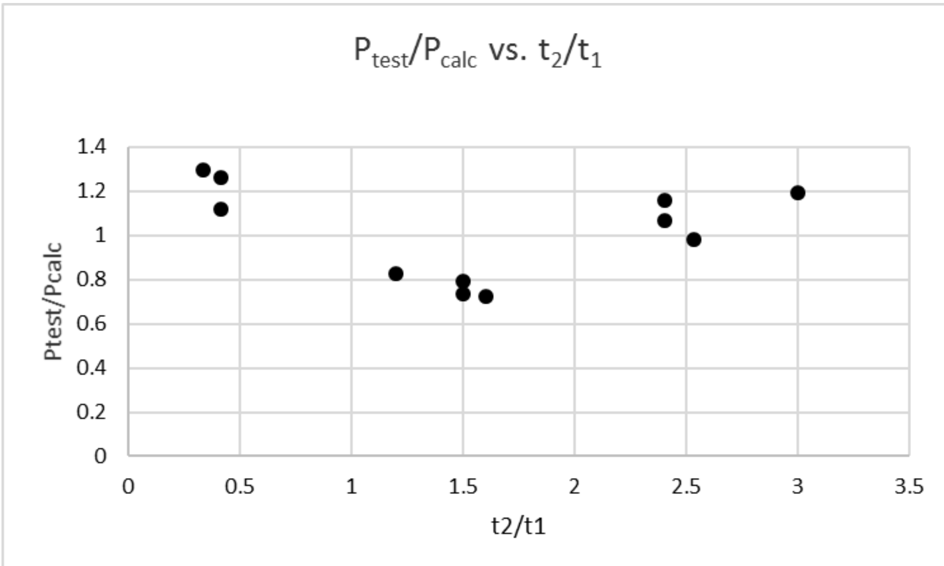

Figure 2.1 Ratio of tested strength to calculated strength versus ratio of bottom sheet thickness to top sheet thickness for the Huynh, Pram, and Hancock (2018)

<u>Section 2.2.4</u> - Koka, E., Yu, W., and LaBoube, R. (1997). “Screw and Welded Connection Behavior Using Structural Grade 80 of A653 Steel (A Preliminary Study).” *Center for Cold-Formed Steel Structures Library*, 115, 1-22.

This report included results of 56 connection tests, 21 of which provided tested loads of single shear screw connections. The authors noted that bearing combined with screw tilting was the most common failure mode among these tests. Of the 21 data points, 6 came from single screw connection tests, 6 came from 2 screw connection tests, 6 came from 3 screw connection tests, and 3 came from 4 screw connection tests. All 21 tests used low-ductility steel. It should be noted that the reported screw dimensions came from the average dimensions of a random sample of 10 of the screws used in these tests. All tests in this report used the same type of screw. A summary of this dataset is included in Table 2-4.

Table 2-4 – Koka, Yu, and LaBoube (1997)

	2016	**2020**
n:	21	21
m:	20	20
C_{φ} (LRFD):	1.52	1.52
C_{φ} (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	0.845	0.845
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.08
V_F:	0.1	0.05
C_p:	1.164	1.164
V_p:	0.089	0.089
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	0.845	0.845
Standard Deviation:	0.075	0.075
Coefficient of Variation:	0.089	0.089
Φ (LRFD):	0.547	0.590
Ω (ASD):	2.923	2.713
Alt Ω:	2.803	2.599
Φ (LSD):	0.447	0.486

<u>Section 2.2.5</u> - Li, Y., Ma, R., and Yao, X. (2010). "Shear Behavior of Screw Connections for Cold-formed Thin-walled Steel Structures." *International Specialty Conference on Cold-Formed Steel Structures*, 6, 493-502.

64 data points were collected from this paper. 9 of these data points came from single screw connection tests, 6 came from 2 screw connection tests, 20 came from 3 screw connection tests, 9 came from 4 screw connection tests, and 20 came from 5 screw connection tests. This report analyzed how screw spacing, number of screws, end distance, and pattern of screws affected shear connection strength. The authors found that connection strength increases with increasing screw spacing up to a spacing of 5 times the screw diameter, from which point it has little effect. This report also found that there is a "group effect" that takes place as the number of screws per connection increases, causing a decrease in strength per screw. All 64 tests used ductile steel. A summary of this dataset is included in the table below. It should be noted that while the average value of test strength divided by calculated strength for this dataset is 0.871 with a low standard deviation of 0.073, the average value of the test strength divided by calculated strength of only the single screw connections from this dataset is 0.946. This indicates that the "group effect" may be the cause of the overall average being lower than expected. A summary of this data set is included in Table 2-5.

Table 2-5 – Li, Ma, and Yao (2010)

	2016	**2020**
n:	64	64
m:	63	63
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	0.871	0.871
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.08
V_F:	0.1	0.05
C_p:	1.049	1.049
V_p:	0.084	0.084
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	0.871	0.871
Standard Deviation:	0.073	0.073
Coefficient of Variation:	0.084	0.084
Φ (LRFD):	0.572	0.617
Ω (ASD):	2.799	2.595
Alt Ω:	2.681	2.487
Φ (LSD):	0.467	0.509

<u>Section 2.2.6</u> - Rogers, C.A. and Hancock, G.J. (1997). "Screwed Connection Tests of Thin G550 and G300 Sheet Steels," *Centre for Advanced Structural Engineering, Department of Civil Engineering, University of Sydney*, 1.

88 data points were collected from this report. 56 of these data points came from 2 screw connection tests, the remaining 32 data points came from 4 screw connection tests. 24 of these tests used ductile steel while the remaining 64 used low-ductility steel. A summary of this dataset is included in Table 2-6. It should be noted that while this dataset consists of multiple screw connections, there is no noticeable "group effect" as noted in Section 2.2.5.

Table 2-6 – Rogers and Hancock (1997)

	2016	**2020**
n:	88	88
m:	87	87
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.012	1.012
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.08
V_F:	0.1	0.05
C_p:	1.035	1.035
V_p:	0.246	0.246
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.012	1.012
Standard Deviation:	0.249	0.249
Coefficient of Variation:	0.246	0.246
Φ (LRFD):	0.487	0.515
Ω (ASD):	3.285	3.107
Alt Ω:	3.148	2.978
Φ (LSD):	0.381	0.406

<u>Section 2.2.7</u> - Moravek, S. (1980). "Shear Test: Teks / 1,2,3,4 and 5 in Various Test Material Combinations." *Buildex Division-Illinois Tools Works, Inc.*, 1-54.

140 data points were collected from this report, all of which came from single screw connection tests using ductile steel. One of these data points was omitted from analysis because the failure mode was not explicitly stated. A summary of this dataset is included in Table 2-7.

Table 2-7 – Moravek (1980)

	2016	**2020**
n:	140	140
m:	139	139
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.127	1.127
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.08
V_F:	0.1	0.05
C_p:	1.022	1.022
V_p:	0.198	0.198
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.127	1.127
Standard Deviation:	0.223	0.223
Coefficient of Variation:	0.198	0.198
Φ (LRFD):	0.609	0.648
Ω (ASD):	2.628	2.471
Alt Ω:	2.518	2.368
Φ (LSD):	0.484	0.519

Section 2.2.8 - Daudet, Randy L. and LaBoube, Roger A. (1996). "Shear Behavior of Self Drilling Screws Used in Low-ductility Steel." *International Specialty Conference on Cold-Formed Steel Structures*, 3, 595-613.

62 data points were collected from this paper, all of which came from single screw connection in single shear tests. 32 of these tests used ductile steel while the remaining 30 tests used low-ductility steel. It should be noted that the writers of this report calculated P_{calc} using an equation they derived on page 599 of the paper, referred to as "Equation 5." This equation does not match the design equations in the AISI S100-16 Standard, therefore the P_{calc} values considered in this report do not match those provided in the paper. A summary of this dataset is included in Table 2-8.

Table 2-8 – Daudet and LaBoube (1996)

	2016	**2020**
n:	62	62
m:	61	61
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.036	1.036
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.08
V_F:	0.1	0.05
C_p:	1.051	1.051
V_p:	0.165	0.165
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.036	1.036
Standard Deviation:	0.171	0.171
Coefficient of Variation:	0.165	0.165
Φ (LRFD):	0.597	0.638
Ω (ASD):	2.678	2.507
Alt Ω:	2.568	2.403
Φ (LSD):	0.479	0.517

Section 2.2.9 - Eastman, R.W. (1976). "Report on Screw Fastened Sheet Steel Connections." *Canadian Steel Industries Construction Council*, 1, 1-30.

160 data points were collected from this report, all of which came from 2-screw connections using ductile steel. A summary of this data set is included in Table 2-9.

Table 2-9 Eastman (1976)

	2016	**2020**
n:	160	160
m:	159	159
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	0.942	0.942
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.08
V_F:	0.1	0.05
C_p:	1.019	1.019
V_p:	0.166	0.166
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	0.942	0.942
Standard Deviation:	0.157	0.157
Coefficient of Variation:	0.166	0.166
Φ (LRFD):	0.544	0.581
Ω (ASD):	2.939	2.752
Alt Ω:	2.819	2.637
Φ (LSD):	0.437	0.471

Section 2.3 - Total Shear Database

In total, 702 tests from 9 different sources were considered. To properly analyze the accuracy of current strength equations, only data points which included screw diameter, base steel thickness of both steel sheets, tensile strengths of both steel sheets, and the ultimate tested strength was included. This data includes both low and ductile steels, and connections with one or multiple screws. The reported test strengths (P_{test}) of all 702 data points were then compared to the nominal shear strengths (P_{calc}) of the connections as calculated by the AISI S100-16 Standard strength equations. This analysis led to an average value of P_{test}/P_{calc} of 1.022, with a Load and Resistance Factor Design (LRFD) resistance factor of 0.571 and an Allowable Strength Design (ASD) factor of safety of 2.800. This data suggests that the current LRFD resistance factor of 0.50 could potentially be increased to 0.55. Similarly, this analysis led to a Limit States Design (LSD) resistance factor of 0.456 that suggests that the current LSD resistance factor of 0.40 could be increased to 0.45 as well. The statistics of the entire data set are found in Table 2-10.

Table 2-10 - Total Shear Database

	2016	2020
n:	701	701
m:	700	700
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.022	1.022
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.08
V_F:	0.1	0.05
C_p:	1.004	1.004
V_p:	0.212	0.212
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.022	1.022
Standard Deviation:	0.216	0.216
Coefficient of Variation:	0.212	0.212
Φ (LRFD):	0.538	0.571
Ω (ASD):	2.975	2.800
Alt Ω:	2.850	2.685
Φ (LSD):	0.426	0.456

Section 2.4 - Further Analysis of Shear Data

Section 2.4.1 - One Screw Versus Multiple Screws

To determine whether the strength of a steel-to-steel screw connection increases linearly with the number of screws used in the connection, 702 data points were split into two groups: single screw connections and multiple screw connections. Statistical analyses were performed on both groups, with the results compared to determine if there was a significant difference in the results. The tested strengths of multiple-screw connections were divided by the number of screws to determine strength-per-screw of the connection. The number of screws in the multiple screw connections observed ranged from 2 to 5 screws, in a linear pattern, parallel to the load.

Of the 702 data points considered, 373 were single-screw connections. The average value of P_{test}/P_{calc} for single-screw connections was 1.075, with a LRFD resistance factor of 0.607 and factor of safety of 2.636, and a LSD resistance factor of 0.486.

The remaining 329 data points were multiple-screw connections, ranging from 2 to 5 screws per connection. The average value of P_{test}/P_{calc} for multiple screw connections was 0.965, with a LRFD resistance factor of 0.550 and factor of safety of 2.908, and with a LSD resistance factor of 0.441.

When comparing these values of P_{test}/P_{calc}, it becomes apparent that the current standard strength equation tends to slightly over predict the shear strength of screws in multiple-screw connections. This is possibly due to the “group effect” discussed by Li, Ma, and Yao (2010). Further research into the relationship between the number of screws and strength of connections may be warranted in order to further understand this “group effect” and adjust the design equations in the AISI S100 Standard. However, since the apparent group effect appears to be relatively small, it may be acceptable to consider that this group effect can be covered by using the resistance factor for multiple screw connections.

Table 2-11 Single Screw versus Multiple Screws

	Multiple Screws		Single Screw	
	2016	2020	2016	2020
n:	329	329	373	373
m:	328	328	372	372
C_φ (LRFD):	1.52	1.52	1.52	1.52
C_φ (LSD):	1.42	1.42	1.42	1.42
M_m:	1.1	1.1	1.1	1.1
F_m:	1	1	1	1
P_m:	0.965	0.965	1.075	1.075
βo (LRFD):	3.5	3.5	3.5	3.5
βo (LSD):	4	4	4	4
V_M:	0.1	0.08	0.1	0.08
V_F:	0.1	0.05	0.1	0.05
C_p:	1.009	1.009	1.008	1.008
V_p:	0.203	0.203	0.207	0.207
V_Q:	0.21	0.21	0.21	0.21
Mean P_{test}/P_{calc}	0.965	0.965	1.075	1.075
Standard Deviation:	0.196	0.196	0.222	0.222
Coefficient of Variation:	0.203	0.203	0.207	0.207
Φ (LRFD):	0.517	0.550	0.571	0.607
Ω (ASD):	3.092	2.908	2.800	2.636
Alt Ω:	2.966	2.786	2.685	2.525
Φ (LSD):	0.411	0.441	0.453	0.486

Since screws are rarely used in a single screw application, the Committee may want to consider the difference in the LRFD Resistance Factor of 0.607 for a single screw and 0.550 for multiple screws of 0.057 to be significant. However, using the multiple screw factors (Φ = 0.55 for LRFD) is supported and reasonable.

Section 2.4.2 - Low-ductility Versus Ductile Steel

To investigate the influence of ductility of steel sheets on the strength of screw connections, the 702 data points were divided into two groups: low-ductility steel connections, and ductile steel connections. For the purposes of this study, low-ductility steel was defined as steel in which the ratio of ultimate strength to yield strength is less than 1.1. All tests observed in this study consisted of either both sheets being low-ductility or both sheets being ductile, no mixed ductility tests were reviewed.

Out of the 702 collected data points, 126 met the criteria to be considered low-ductility. Statistical analysis of this data (Table 2-12) resulted in an average P_{test}/P_{calc} value of 0.946, with a LRFD resistance factor of 0.551 and a factor of safety of 2.902, and with a LSD resistance factor of 0.443.

The remaining 576 data points were considered ductile. This data resulted in an average P_{test}/P_{calc} value of 1.039 with a LRFD resistance factor of 0.581 and a factor of safety of 2.756, and with a LSD resistance factor of 0.464.

When comparing these data sets, there appears to be no significant difference. This implies that ductility does not play a major role in determining the strength of steel-to-steel screw connections and therefore does not need to be considered in revising the existing shear strength equations.

The data for low-ductility steel was further analyzed by plotting the ratio of t_2/t_1 versus P_{test}/P_{calc}. When the larger dataset is looked at, the dip in the ratio of P_{test}/P_{calc} at intermediate ratios of t_2/t_1 shown in Huynh, M., Pham, C., and Hancock, G. (2018) is not apparent.

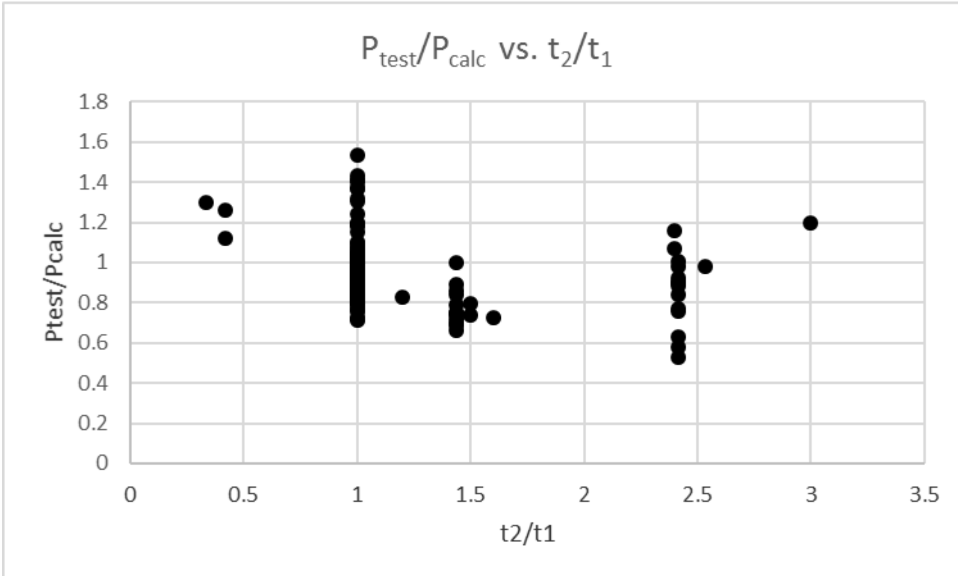

Figure 2.2 Effect of thickness ratio on low-ductility data

Table 2-12 - Low versus Ductile

	Low-ductility		**Ductile**	
	2016	**2020**	**2016**	**2020**
n:	126	126	576	576
m:	125	125	575	575
C_{φ} (LRFD):	1.52	1.52	1.52	1.52
C_{φ} (LSD):	1.42	1.42	1.42	1.42
M_m:	1.1	1.1	1.1	1.1
F_m:	1	1	1	1
P_m:	0.946	0.946	1.039	1.039
βo (LRFD):	3.5	3.5	3.5	3.5
βo (LSD):	4	4	4	4
V_M:	0.1	0.08	0.1	0.08
V_F:	0.1	0.05	0.1	0.05
C_p:	1.024	1.024	1.005	1.005
V_p:	0.192	0.192	0.212	0.212
V_Q:	0.21	0.21	0.21	0.21
Mean P_{test}/P_{calc}	0.946	0.946	1.039	1.039
Standard Deviation:	0.181	0.181	0.22	0.22
Coefficient of Variation:	0.192	0.192	0.212	0.212
Φ (LRFD):	0.518	0.551	0.547	0.581
Ω (ASD):	3.090	2.902	2.928	2.756
Alt Ω:	2.960	2.783	2.803	2.639
Φ (LSD):	0.412	0.443	0.433	0.464

Section 2.4.3 - Thin Sheet Thickness

To determine the effect of sheet thickness on the accuracy of current strength equations, cases in which either steel sheet had a thickness of less than 0.028 inches, were isolated and analyzed. In total, 247 data points met this criterion and are shown in Table 2-13. Of these 247 tests, 116 consisted of connections in which both sheets qualified as thin sheets. For the remaining 131 tests, only the sheet in contact with the screw head qualified as a thin sheet. No significant differences were observed between these two cases. Statistical analyses of this dataset of thin sheet connections revealed an average P_{test}/P_{calc} value of 0.980, with a LRFD resistance factor of 0.528 and a factor of safety of 3.028, and with a LSD resistance factor of 0.420. This data suggests that these thin sheet cases are not significantly different from the overall dataset. This implies that thin sheet steel-to-steel screw connections follow the same patterns as other thicknesses and therefore do not need special consideration when determining design equations in the AISI S100 Standard.

Table 2-13 Sheet Thickness Less than 0.028 inches.

	Thin Sheet		All Data	
	2016	**2020**	**2016**	**2020**
n:	247	247	702	702
m:	246	246	701	701
C_φ (LRFD):	1.52	1.52	1.52	1.52
C_φ (LSD):	1.42	1.42	1.42	1.42
M_m:	1.1	1.1	1.1	1.1
F_m:	1	1	1	1
P_m:	0.980	0.980	1.022	1.022
βo (LRFD):	3.5	3.5	3.5	3.5
βo (LSD):	4	4	4	4
V_M:	0.1	0.08	0.1	0.08
V_F:	0.1	0.05	0.1	0.05
C_p:	1.012	1.012	1.004	1.004
V_p:	0.226	0.226	0.212	0.212
V_Q:	0.21	0.21	0.21	0.21
Mean P_{test}/P_{calc}	0.980	0.980	1.022	1.022
Standard Deviation:	0.221	0.221	0.216	0.216
Coefficient of Variation:	0.226	0.226	0.212	0.212
Φ (LRFD):	0.498	0.528	0.538	0.571
Ω (ASD):	3.211	3.028	2.975	2.800
Alt Ω:	3.079	2.902	2.850	2.685
Φ (LSD):	0.393	0.420	0.426	0.456

Section 2.4.4 - Ratio of Sheet Thickness

The final special case that this study investigated involved single screw connections, and looking at the three regimes of shear behavior (bearing, combined bearing and tilting, and tilting). Bearing without tilting is the limit state where the bottom sheet thickness (t_2) is equal to or greater than 2.5 times the top sheet thickness (t_1). 115 data points met this criterion, resulting in an average P_{test}/P_{calc} value of 1.011, with an LRFD resistance factor of 0.568 and factor of safety of 2.815, and with a LSD resistance factor of 0.454.

Tilting without bearing is the limit state where the bottom sheet thickness (t_2) is less than or equal to the top sheet thickness (t_1). Table 2-14 shows that 352 data points met this criterion, resulting in an average P_{test}/P_{calc} value of 1.008, with an LRFD resistance factor of 0.585 and factor of safety of 2.733, and with a LSD resistance factor of 0.470.

Combined tilting and bearing is the limit state that is in the intermediate range. 235 data points met this criterion, resulting in an average P_{test}/P_{calc} value of 1.049, with an LRFD resistance factor of 0.555 and factor of safety of 2.855, and with a LSD resistance factor of 0.439.

Comparing these datasets (Figure 2.3) shows no significant difference, indicating the reliability and performance of screw connections is not adversely affected by tilting. This is somewhat surprising, because it might be intuitively thought that tilting might be slightly less reliable.

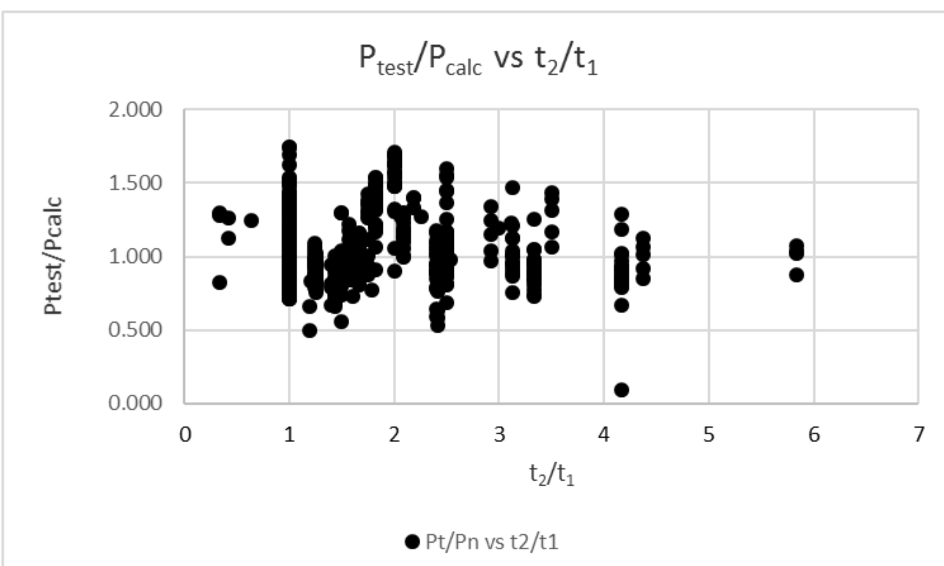

Figure 2.3 Effect of ratio of thickness for all data.

Table 2-14 - Shear Data Divided by Relative Sheet Thickness

	$t_2/t_1 \leq 1$		$1 < t_2/t_1 < 2.5$		$t_2/t_1 \geq 2.5$	
	2016	**2020**	**2016**	**2020**	**2016**	**2020**
n:	352	352	235	235	115	115
m:	351	351	234	234	114	114
C_φ (LRFD):	1.52	1.52	1.52	1.52	1.52	1.52
C_φ (LSD):	1.42	1.42	1.42	1.42	1.42	1.42
M_m:	1.1	1.1	1.1	1.1	1.1	1.1
F_m:	1	1	1	1	1	1
P_m:	1.008	1.008	1.049	1.049	1.011	1.011
βo (LRFD):	3.5	3.5	3.5	3.5	3.5	3.5
βo (LSD):	4	4	4	4	4	4
V_M:	0.1	0.08	0.1	0.08	0.1	0.08
V_F:	0.1	0.05	0.1	0.05	0.1	0.05
C_p:	1.009	1.009	1.013	1.013	1.027	1.027
V_p:	0.195	0.195	0.234	0.234	0.207	0.207
V_Q:	0.21	0.21	0.21	0.21	0.21	0.21
Mean P_{test}/P_{calc}	1.008	1.008	1.049	1.049	1.011	1.011
Standard Deviation:	0.196	0.196	0.245	0.245	0.21	0.21
Coefficient of Variation:	0.195	0.195	0.234	0.234	0.207	0.207
Φ (LRFD):	0.550	0.585	0.524	0.555	0.535	0.568
Ω (ASD):	2.909	2.733	3.056	2.885	2.991	2.815
Alt Ω:	2.788	2.619	2.926	2.765	2.866	2.698
Φ (LSD):	0.438	0.470	0.411	0.439	0.424	0.454

Section 2.5 - Overall Impressions and Recommendations

1. For the limit state of shear, the test data indicates that the current nominal strength prediction equations in AISI S100-16 do not need to be revised. This is a positive outcome, because these equations are also used in the AISI S310-16 Standard and changing these equations would have major implications for that Standard.

2. For the limit state of shear, the analysis of the entire data set, and of individual conditions, the resistance factor for both LRFD and LSD could be increased by 0.05 to 0.55 and 0.45 respectively. If the resistance factor is changed, there will be no effect on the AISI S310-16 Standard, because diaphragms receive their own system-based resistance factor.

3. For screws loaded in shear, the alternate factor of safety using the live to dead load ratio of 5:1 which is the basis for the rest of the AISI S100-16, should be strongly considered. This would decrease the factor of safety from the current 3.00 to 2.80.

Chapter 3 – Pull-over

Section 3.1 – Introduction

Phase 2 of this study examined the limit state of pull-over of steel-to-steel screw connections. This section of the study consists of an analysis of existing test data from screw connections which failed in pull-over to assess the legitimacy of the current pull-over strength equations, resistance factors, and factors of safety. In this chapter, calculated strength of connections was determined in two ways. “Method A” used the reported ultimate strength in the nominal pull-over strength equation for all cases. “Method B” set the ultimate strength equal to 62 ksi for connections with low-ductility steel, while using the reported ultimate strength for ductile connections.

As currently contained in the AISI S100-16 Standard, the nominal pull-over strength of steel sheet per screw, P_{nov}, shall be determined by the following calculations:

$$P_{nov} = 1.5t_1d'_wF_{u1} \qquad \text{(Eq. J4.4.2-1)}$$

Where

d'_w = Effective pull-over diameter determined in accordance with (a), (b), or (c) as follows:

(a) For a round head, hex head, pancake screw washer head, or hex washer head screw with an independent and solid steel washer beneath the screw head:

$$d'_w = d_h + 2t_w + t_1 \leq d_w \qquad \text{(Eq. J4.4.2-2)}$$

where

t_w = Steel washer thickness

(b) For a round head, a hex head, or a hex washer head screw without an independent washer beneath the screw head:

$d'_w = d_h$ but not larger than ¾ in. (19.1 mm)

(c) For a domed (non-solid and either independent or integral) washer beneath the screw head, it is permitted to use d'_w as calculated in Eq. J4.4.2-2, where t_w is the thickness of the domed washer. In the equation, d'_w shall not exceed ¾ in. (19.1 mm).

It should be noted that all tests observed in this study consist of type (b) as described above.

In performing this study, some items were considered:

1. In accordance with AISI S100-16 Commentary Equation C-B3.2.2-16, the factor of safety, Ω, can be calculated based on the ratio of live loads to dead loads, which is assumed to be equal to 5:1 in this Standard. In this case, Ω can be set equal to 1.5333 divided by Φ. For this report, this calculation will be labeled "Alternate calculation of Ω."

2. In accordance Section K2.1.1 of AISI S100-16 a reliability index of 3.5 was used for LRFD, and a reliability index of 4.0 was used for LSD.

3. Low-ductility steels are defined as having a minimum elongation of less than 10%. See AISI S100-16, Sections A3.1.2 and A3.1.3.

<u>Section 3.2 – Previous Studies</u>

In this section, each individual test report or paper is reported on individually.

<u>Section 3.2.1</u> – Test results group 1 provided by Manufacturer Alpha

54 pull-over test results were provided by Manufacturer Alpha. Of these tests, 30 used low-ductility steel and the remaining 24 used ductile steel. A summary of this dataset is reported in Table 3-1.

Table 3-1 – Manufacturer Alpha Group 1

	Method A	Method B
n:	54	54
m:	53	53
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	0.768	0.968
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.058	1.058
V_p:	0.306	0.183
V_Q:	0.21	0.21
Mean:	0.768	0.968
Standard Deviation:	0.235	0.177
Coefficient of Variation:	0.306	0.183
Φ (LRFD):	0.312	0.537
Ω (ASD):	5.123	2.979
Alt Ω:	4.909	2.855
Φ (LSD):	0.238	0.429

<u>Section 3.2.2</u> – Kreiner, J. (1996). "Static Load Tests For Through-Fastened Metal Roof and Wall Systems." *University of Florida dissertation,* 1-25.

36 usable pull-over test results were obtained from Kreiner's 1996 report. This report also included 24 pull-over tests with eccentric loading, however these were not included in this study as they do not reflect the standard testing conditions of interest. Kreiner's report also included the results of several simulated pull-over strength tests, however this data was omitted from this study as the methods did not follow the standard testing conditions of interest. A summary of this dataset is reported in Table 3-2.

Table 3-2 – Kreiner (1996)

	Method A	Method B
n:	36	36
m:	35	35
$C_φ$ (LRFD):	1.52	1.52
$C_φ$ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.210	1.499
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.090	1.090
V_p:	0.202	0.128
V_Q:	0.21	0.21
Mean:	1.210	1.499
Standard Deviation:	0.245	0.192
Coefficient of Variation:	0.202	0.128
Φ (LRFD):	0.638	0.92
Ω (ASD):	2.507	1.739
Alt Ω:	2.403	1.666
Φ (LSD):	0.506	0.745

Section 3.2.3 – Test results group 2 provided by Manufacturer Alpha

30 pull-over test results were obtained from the second group of test results provided by Manufacturer Alpha. All 30 tests used ductile steel, so as a result only Method A was used to compare tested strengths to predicted strengths. A summary of this dataset is reported in Table 3-3.

Table 3-3 Manufacturer Alpha Group 2

	Method A
n:	30
m:	29
Cφ (LRFD):	1.52
Cφ (LSD):	1.42
Mm:	1.1
Fm:	1
Pm:	0.832
βo (LRFD):	3.5
βo (LSD):	4
VM:	0.1
VF:	0.1
Cp:	1.11
Vp:	0.104
VQ:	0.21
Mean:	0.832
Standard Deviation:	0.086
Coefficient of Variation:	0.104
Φ (LRFD):	0.53
Ω (ASD):	3.02
Alt Ω:	2.894
Φ (LSD):	0.431

Section 3.2.4 – Test results provided by Manufacturer Bravo

11 pull-over test results were provided by Manufacturer Bravo. Of these 11 tests, 3 used low-ductility steel while the remaining 8 used ductile steel. A summary of this dataset is reported in Table 3-4 below.

Table 3-4 – Manufacturer Bravo

	Method A	Method B
n:	11	11
m:	10	10
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	0.934	0.983
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.364	1.364
V_p:	0.469	0.368
V_Q:	0.21	0.21
Mean:	0.934	0.983
Standard Deviation:	0.438	0.361
Coefficient of Variation:	0.469	0.368
Φ (LRFD):	0.189	0.287
Ω (ASD):	8.464	5.575
Alt Ω:	8.111	5.343
Φ (LSD):	0.131	0.209

Section 3.2.5 – Test results provided by Manufacturer Charlie

12 pull-over strength test results were provided by Manufacturer Charlie. All 12 tests used ductile steel, so as a result only Method A was used to compare tested strengths to predicted strengths. A summary of this dataset is report in Table 3-5 below.

Table 3-5 – Manufacturer Charlie

	Method A
n:	12
m:	11
C_φ (LRFD):	1.52
C_φ (LSD):	1.42
M_m:	1.1
F_m:	1
P_m:	1.172
βo (LRFD):	3.5
βo (LSD):	4
V_M:	0.1
V_F:	0.1
C_p:	1.324
V_p:	0.110
V_Q:	0.21
Mean:	1.172
Standard Deviation:	0.129
Coefficient of Variation:	0.110
Φ (LRFD):	0.728
Ω (ASD):	2.198
Alt Ω:	2.106
Φ (LSD):	0.590

Section 3.3 – Total Pull-Over Database

In total, 143 tests from 5 different sources were considered. Only tests which conformed to the AISI S905 and reported t_1, d'_w, and F_{u1} were considered. Of the 143 tests considered, 48 used low-ductility steel. The remaining 95 tests used ductile steel. This guaranteed a legitimate analysis of the current strength equations. A summary of the total pull-over database is reported in Table 3-6 below.

Table 3-6 – Total Pull-Over Database

	Method A	Method B
n:	143	143
m:	142	142
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	0.939	1.091
βo (LRFD):	3.5	3.5
βo (LSD):	4	4
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.021	1.021
V_p:	0.317	0.284
V_Q:	0.21	0.21
Mean:	0.939	1.091
Standard Deviation:	0.297	0.310
Coefficient of Variation:	0.317	0.284
Φ (LRFD):	0.377	0.478
Ω (ASD):	4.249	3.350
Alt Ω:	4.072	3.211
Φ (LSD):	0.287	0.368

Section 3.4 – Further Analysis of Pull-Over Data

Section 3.4.1 – Low-ductility Versus Ductile

To determine the effect of ductility on the pull-over strength of a steel-to-steel screw connection, the entire pull-over database was divided into two groups: connections with ductile steel and connections with low-ductility steel. Of the 143 tests, 95 used ductile steel while the remaining 48 used low-ductility steel. The low-ductility data set was analyzed using both Method A (F_u = Actual) and Method B (F_u = 62 ksi) as discussed in the introduction of this chapter.

Using Method A for low-ductility steels, the analysis yielded an average P_{test}/P_{calc} value of 0.691, an LRFD Φ of 0.264, an ASD Ω of 6.062, an alternate Ω of 5.809, and an LSD Φ of 0.200.

Using Method B provided improved results, with an average P_{test}/P_{calc} value of 1.144, an LRFD Φ of 0.401, an ASD Ω of 3.986, an Alternate Ω of 3.820, and an LSD Φ of 0.300.

Comparatively, analysis of the ductile dataset found an average P_{test}/P_{calc} value of 1.065, an LRFD Φ of 0.532, an ASD Ω of 3.010, an Alternate Ω of 2.885, and an LSD Φ of 0.418.

This data suggests that the current strength equations are good predictors for steel-to-steel screw connections with either ductile or low-ductility steel (if F_u is limited), but because of the larger scatter in the low-ductility test data, a lower resistance factor for low-ductility steel is warranted. A summary of these datasets is reported in Table 3-7.

Table 3-7 – Ductile Versus Low-ductility Pull-Over

	Ductile	Low-ductility	
	Method A	Method A	Method B
n:	95	48	48
m:	94	47	47
C_φ (LRFD):	1.52	1.52	1.52
C_φ (LSD):	1.42	1.42	1.42
M_m:	1.1	1.1	1.1
F_m:	1	1	1
P_m:	1.065	0.691	1.144
βo (LRFD):	3.5	3.5	3.5
βo (LSD):	4	4	4
V_M:	0.1	0.1	0.1
V_F:	0.1	0.1	0.1
C_p:	1.032	1.066	1.066
V_p:	0.231	0.327	0.356
V_Q:	0.21	0.21	0.21
Mean:	1.065	0.691	1.144
Standard Deviation:	0.246	0.226	0.407
Coefficient of Variation:	0.231	0.327	0.356
Φ (LRFD):	0.532	0.264	0.401
Ω (ASD):	3.010	6.062	3.986
Alt Ω:	2.885	5.809	3.820
Φ (LSD):	0.418	0.200	0.300

In Figures 3.1 to 3.4, the ratio of tested strength to predicted strength is compared to the thickness of the pull-over sheet for all data, for ductile data, for low-ductility data using given ultimate strength, and for low-ductility data using an ultimate strength value of 62 ksi. No significant trends were observed, though it should be noted that setting the ultimate strength equal to 62 ksi for low-ductility steels brought the ratios of tested strength to predicted strength closer to 1.

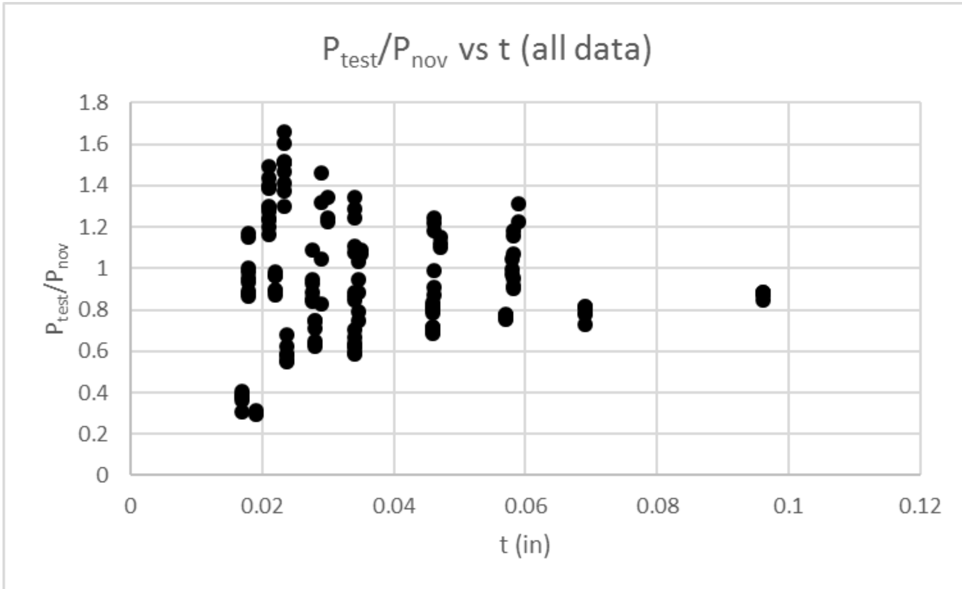

Figure 3.1 – Tested strength to nominal strength ratio versus thickness for all data

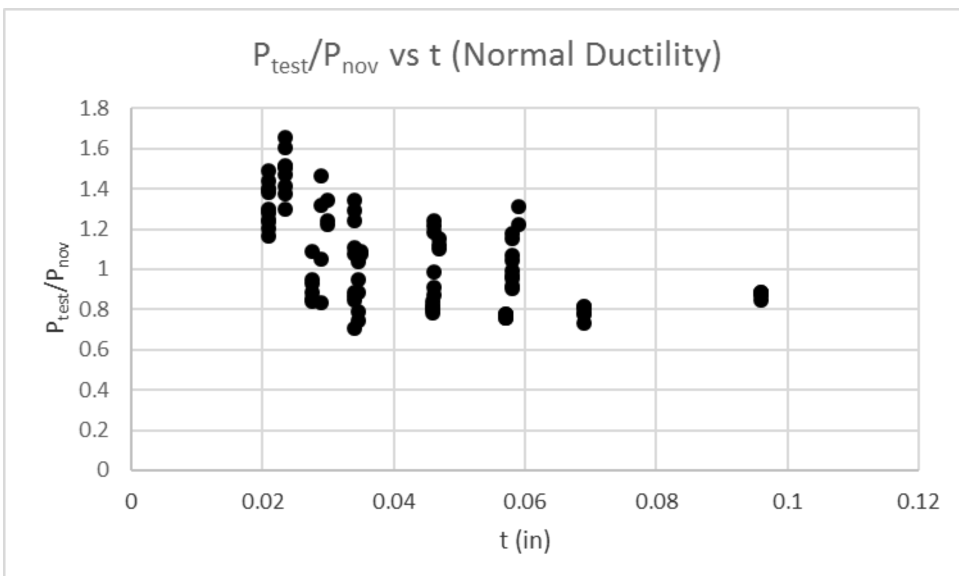

Figure 3.2 – Tested strength to nominal strength ratio versus thickness for ductile

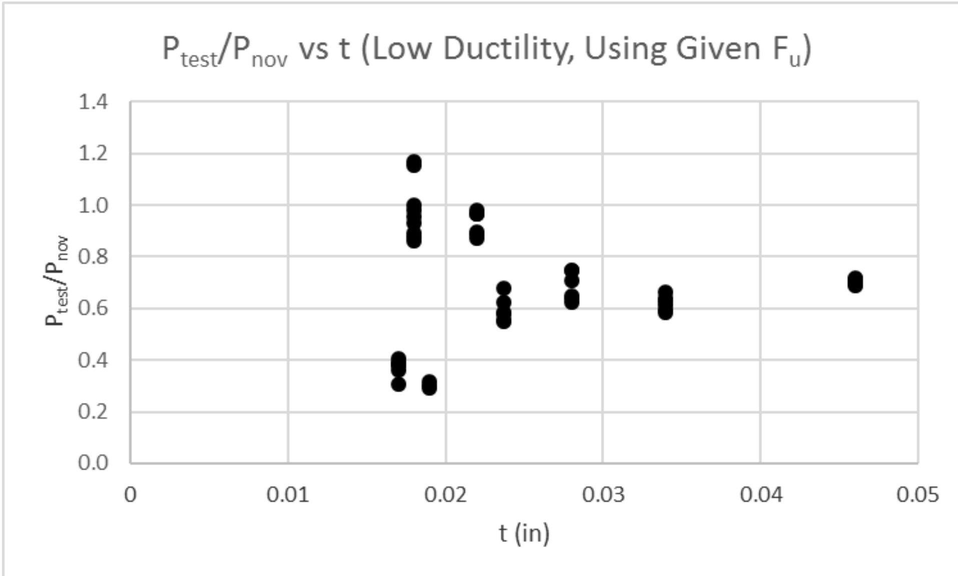

Figure 3.3 – Tested strength to nominal strength ratio versus thickness for low-ductility data (using given F_u Value)

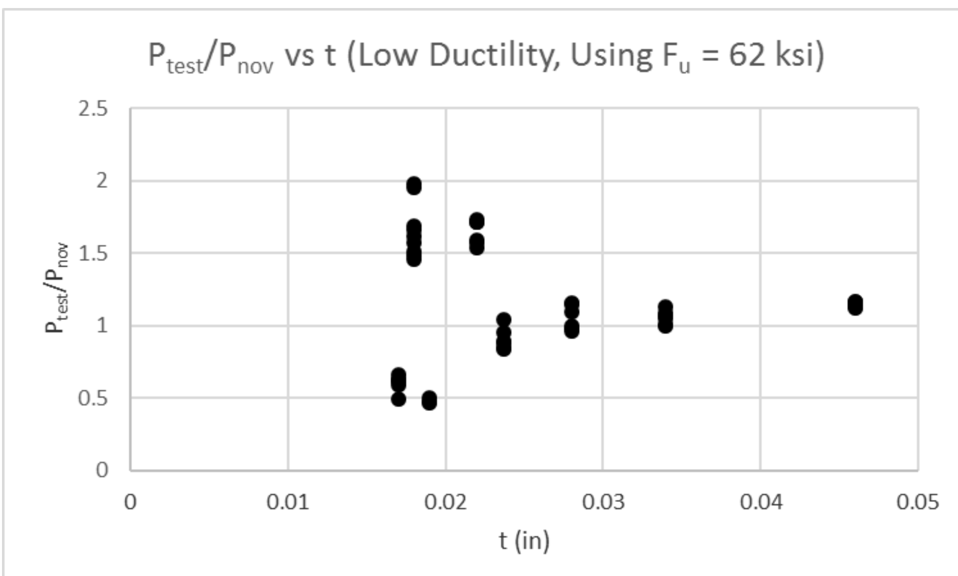

Figure 3.4 – Tested strength to nominal strength ratio versus thickness for low-ductility data (using F_u = 62 ksi)

Section 3.4.2 – Low-ductility Data Split According to Sheet Thickness

During analysis of the low-ductility pull-over data, it was noted that splitting the data into groups in which sheet thickness was greater than or equal to 0.023 inches and tests in which sheet thickness was less than 0.023 inches allows for higher resistance factor values to be retained for thicker low-ductility steels. Setting the break at 0.023 inches fit the data well, and allowed for the break to occur below a 24 gage nominal thickness. A summary of this data split is included in Table 3-8 below.

The statistics for the sheet less than 0.023 inches shows that there is a lot of scatter in the test data. This might be expected because the amount of clamping of the sheet by the screw head might be a key variable in the behavior of the connection. Therefore, for sheet thickness less than 0.023 inches, two recommendations are made. The first column uses the current nominal strength equation for pullover, which results is an LRFD resistance factor of 0.316. This might not be palatable. The second column uses a modified nominal strength equation where the nominal strength is modified by a factor of 0.60. This leads to an LRFD resistance factor of 0.527.

Alternate $P_{nov} = 0.60\ (1.5t_1d'_wF_{u1}) = 0.90t_1d'_wF_{u1}$

The committee will need to determine if the desire is to maintain the current nominal strength equation, and use a resistance factor that basically says “we don’t know how to accurately determine the strength,” or a reduced nominal resistance equation that hides the fact that we really don’t know what we are doing for these thin, low-ductility sheets.

Table 3-8 Low-ductility Data Split According to Sheet Thickness

	Low-ductility (Method B)		Alt P_{nov}
	$t \geq 0.023$ in	$t < 0.023$ in	$t < 0.023$ in
n:	24	24	24
m:	23	23	23
C_φ (LRFD):	1.52	1.52	1.52
C_φ (LSD):	1.42	1.42	1.42
M_m:	1.1	1.1	1.1
F_m:	1	1	1
P_m:	1.044	1.244	2.074
βo (LRFD):	3.5	3.5	3.5
βo (LSD):	4	4	4
V_M:	0.1	0.1	0.1
V_F:	0.1	0.1	0.1
C_p:	1.141	1.141	1.414
V_p:	0.101	0.445	0.445
V_Q:	0.21	0.21	0.21
Mean:	1.044	1.244	2.073
Standard Deviation:	0.105	0.553	0.992
Coefficient of Variation:	0.101	0.445	0.444
Φ (LRFD):	0.666	0.316	0.527
Ω (ASD):	2.402	5.059	3.036
Alt Ω:	2.302	4.848	2.909
Φ (LSD):	0.542	0.226	0.376

Section 3.5 – Overall Impressions and Recommendations

1. For the limit state of pull-over with ductile steel, as determined by a pull-over test that conforms to the AISI S905 Standard, the current pull-over equation and resistance factor and factor of safety can be adjusted as follows: the LRFD resistance factor for this case can be set to 0.55, the ASD factor of safety can be set to 2.90, and the LSD resistance factor can be set to 0.40. These resistance factor values and this factor of safety can also be applied to the limit state of pull-over for low-ductility steel with a sheet thickness equal to or greater than 0.023 inches.

2. For the limit state of pull-over with low-ductility steel, as determined by a pull-over test that conforms to the AISI S905, the existing pull-over equation should continue to limit F_u to the lesser of $0.75F_u$ or 62 ksi. Additionally, in the case of pull-over failure for low-ductility, thin sheet ($t < 0.023$ inches) connections, the LRFD resistance factor can be set to 0.30, the ASD factor of safety can be set to 4.85, and the LSD resistance factor can be set to 0.20. Alternately, for these thin low-ductility sheets, the nominal resistance equation should be reduced by a factor of 0.6 and the LRFD resistance factor can be set to 0.55 the ASD factor of safety can be set to 2.90, and the LSD resistance factor can be set to 0.40.

3. The effect of panel geometry should be reviewed. The recommendations of Kreiner (1996) should be seriously considered for inclusion in the AISI S100 Standard.

Chapter 4 – Pull-Out

Section 4.1 – Introduction

Phase 2 of this study examined connections that failed in pull-out. This portion of the study performed an analysis of existing test data from screw connections failing in pull-out to determine if the current pull-out strength equations, resistance factors, and factors of safety need to be revised. This study focused solely on test data from 2-ply steel-to-steel screw connection strength tests. The pull-out data observed was divided into low-ductility and ductile connections to determine if ductility affected the accuracy of the standard equations. However, in real-world applications low-ductility connections are rarely used in situations where they will fail in pull-out. Because of this, any recommendations determined in this study primarily focus on ductile connections.

As currently contained in the AISI S100-16 Standard, the nominal pull-out strength of sheet per screw shall be determined by the following:

$P_{not} = 0.85 t_c d F_{u2}$ AISI S100-16 Eq. J4.4.1-1

Where:

P_{not} = Nominal pull-out strength of sheet per screw

t_c = Thickness of sheet not in contact with screw head or washer

d = Nominal screw diameter

F_{u2} = Nominal tensile strength of member not in contact with screw head or washer

In performing this study, the following items were considered:

1. In accordance with AISI S100-16 Commentary Equation C-B3.2.2-16, the factor of safety, Ω, can be calculated based on the ratio of live load to dead load, which is assumed to be equal to 5:1 in this Standard. In this case, Ω can be set equal to 1.5333 divided by Φ. For this report, this calculation will be labeled "Alternate calculation of Ω."
2. In accordance with Section K2.1.1 of AISI S100-16 a reliability index of 3.5 was used for LRFD, and a reliability index of 4.0 was used for LSD.
3. Low-ductility steels are defined as having a minimum elongation of less than 10%. See AISI S100-16, Sections A3.1.2 and A3.1.3.

<u>Section 4.2 – Previous Studies</u>

In this section, each individual test report or paper is reported individually.

<u>Section 4.2.1</u> – Test Results Provided by Manufacturer Alpha Set 2

30 data points were collected from this report. All 30 data points consisted of ductile steel connections. A summary of this dataset is reported in Table 4-1.

Table 4-1 Manufacturer Alpha

n:	30
m:	29
C_φ (LRFD):	1.52
C_φ (LSD):	1.42
M_m:	1.1
F_m:	1
P_m:	0.824
βo (LRFD):	3.5
βo (LSD):	4.0
V_M:	0.1
V_F:	0.1
C_p:	1.110
V_p:	0.131
V_Q:	0.21
Mean P_{test}/P_{calc}	0.824
Standard Deviation:	0.108
Coefficient of Variation:	0.131
Φ (LRFD):	0.502
Ω (ASD):	3.187
Alt Ω:	3.054
Φ (LSD):	0.406

Section 4.2.2 - Test Results Provided by Manufacturer Delta

114 data points were obtained by Manufacturer Delta. All 114 tests consisted of ductile steel connections. A summary of this dataset is reported in Table 4-2.

Table 4-2 Manufacturer Delta

n:	114
m:	113
C_φ (LRFD):	1.52
C_φ (LSD):	1.42
M_m:	1.1
F_m:	1
P_m:	1.096
βo (LRFD):	3.5
βo (LSD):	4.0
V_M:	0.1
V_F:	0.1
C_p:	1.027
V_p:	0.205
V_Q:	0.21
Mean P_{test}/P_{calc}	1.096
Standard Deviation:	0.224
Coefficient of Variation:	0.205
Φ (LRFD):	0.583
Ω (ASD):	2.744
Alt Ω:	2.630
Φ (LSD):	0.462

Section 4.2.3 – Test Results Provided by Manufacturer Bravo

137 data points were obtained from Manufacturer Bravo. All 137 tests consisted of ductile steel connections. A summary of this dataset is reported in Table 4-3.

Table 4-3 Manufacturer Bravo

n:	137
m:	136
C_φ (LRFD):	1.52
C_φ (LSD):	1.42
M_m:	1.1
F_m:	1
P_m:	1.022
βo (LRFD):	3.5
βo (LSD):	4.0
V_M:	0.1
V_F:	0.1
C_p:	1.022
V_p:	0.189
V_Q:	0.21
Mean P_{test}/P_{calc}	1.022
Standard Deviation:	0.193
Coefficient of Variation:	0.189
Φ (LRFD):	0.563
Ω (ASD):	2.840
Alt Ω:	2.722
Φ (LSD):	0.449

<u>Section 4.2.4</u> - Sivapathasundaram, M. and Mahendran, M. "Localized Screw Connection Failures in Cold-formed Steel Roofing Systems." *Australian Research Council*, 1-15.

54 data points were collected from this report. 27 of these tests consisted of ductile steel connections. The remaining 27 tests used low-ductility steel connections. The tests conducted in this report did not exactly follow the AISI S905 standard pull-out test procedure, however the methods used were similar enough to the standard that the results were deemed valid for inclusion in this study. It is worth noting that all low-ductility pull-out data came from this single report. A summary of this dataset is included in Table 4-4 below. Figure 4-1 comes directly from this report and demonstrates how this test differs from the AISI S905 standard pull-out test procedure.

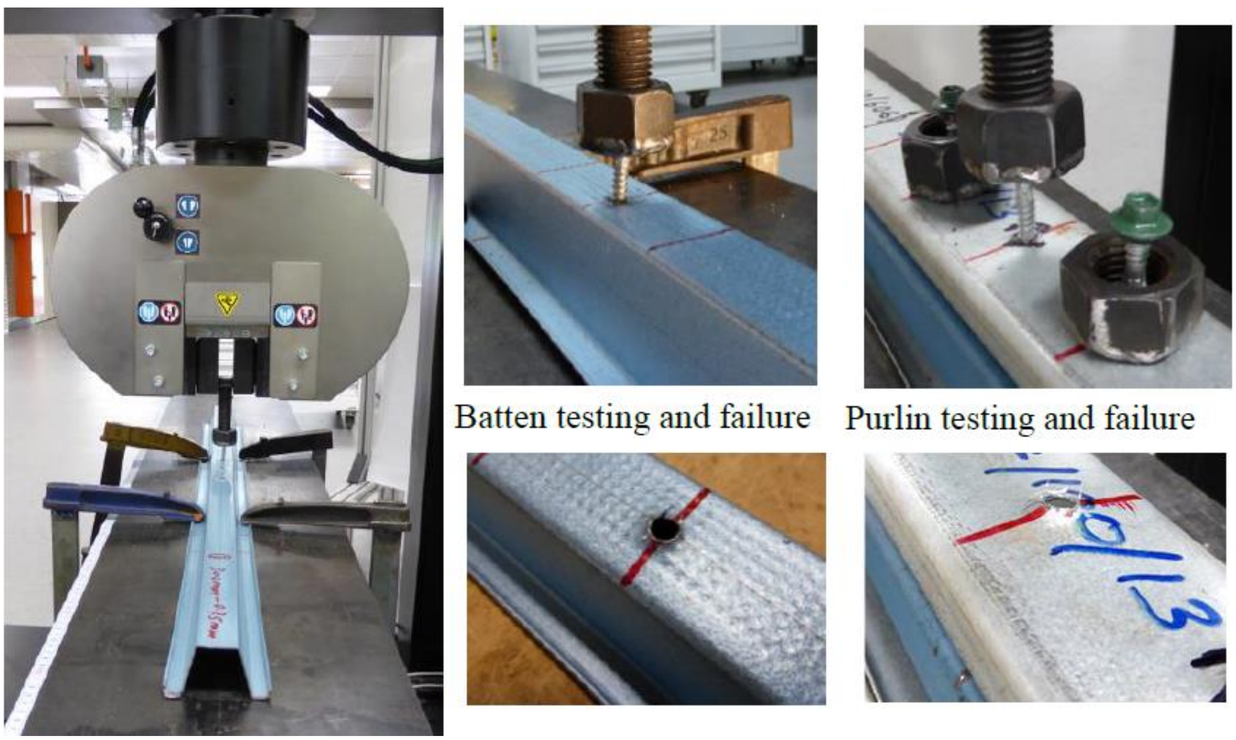

Figure 4.1 Sivapathasundaram and Mahendran pull-out test

Table 4-4 Sivapathasundaram and Mahendran

n:	54
m:	53
C_φ (LRFD):	1.52
C_φ (LSD):	1.42
M_m:	1.1
F_m:	1
P_m:	1.102
βo (LRFD):	3.5
βo (LSD):	4.0
V_M:	0.1
V_F:	0.1
C_p:	1.058
V_p:	0.218
V_Q:	0.21
Mean P_{test}/P_{calc}	1.102
Standard Deviation:	0.240
Coefficient of Variation:	0.218
Φ (LRFD):	0.564
Ω (ASD):	2.835
Alt Ω:	2.717
Φ (LSD):	0.445

Section 4.3 – Total Pull-Out Database

In total, 335 tests from 4 different sources were considered. The reported test strengths (P_{test}) of all 335 data points were then compared to the nominal pull-out strengths (P_{calc}) of the connections as calculated by the AISI S100-16 Standard strength equations. This analysis led to an average P_{test}/P_{calc} value of 1.038, with an LRFD resistance factor of 0.548, an ASD factor of safety of 2.918, and an LSD resistance factor of 0.434. Values of P_{test}/P_{calc} were plotted against sheet thickness to determine if any significant relationship between the two existed. As shown in Figure 4.2, P_{test}/P_{calc} values tend to increase as sheet thickness increases. Figure 4.3, which plots P_{test}/P_{calc} versus d/t (screw diameter versus sheet thickness) shows the inverse relationship as d/t increases. This relationship is addressed in the following section. The statistics of the entire data set are found in Table 4-5.

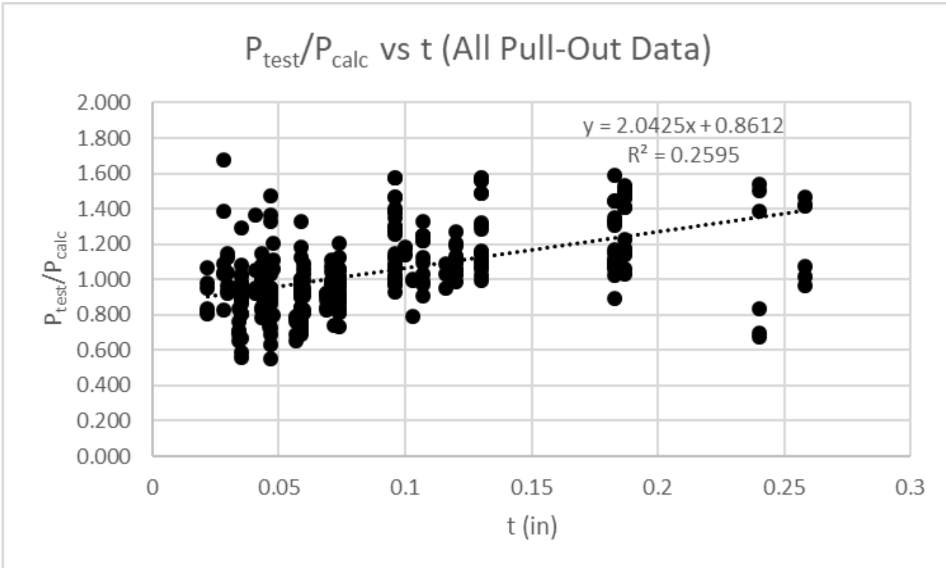

Figure 4.2 Effect of thickness for all data

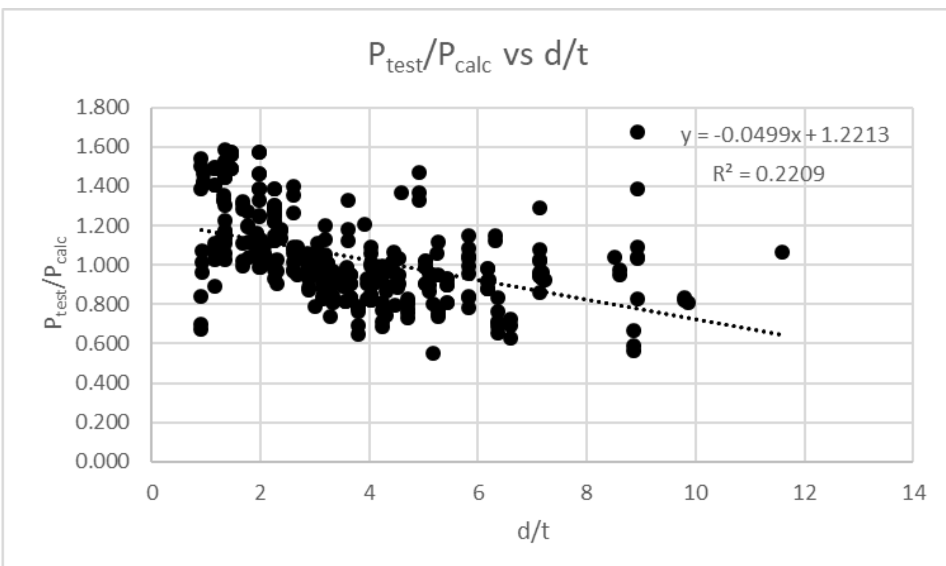

Figure 4.3 P_{test}/P_{calc} versus d/t

Table 4-5 Total Pull-Out Database

n:	335
m:	334
C_{φ} (LRFD):	1.52
C_{φ} (LSD):	1.42
M_m:	1.1
F_m:	1
P_m:	1.038
βo (LRFD):	3.5
βo (LSD):	4.0
V_M:	0.1
V_F:	0.1
C_p:	1.009
V_p:	0.218
V_Q:	0.21
Mean P_{test}/P_{calc}	1.038
Standard Deviation:	0.218
Coefficient of Variation:	0.210
Φ (LRFD):	0.548
Ω (ASD):	2.918
Alt Ω:	2.797
Φ (LSD):	0.434

Section 4.4 – Adjustments to Nominal Pull-Out Strength Equation

Based on observations of the effects of sheet thickness on values of P_{test}/P_{calc}, an adjustment factor of $1.63t_2^{0.18}$ was multiplied into the standard nominal pull-out strength equation. The effects of this adjustment are examined in the following subsections.

Section 4.4.1 – Effect of Adjustment on All Data

Figure 4-2 below demonstrates how the adjustment factor accounts for the relationship between sheet thickness and P_{test}/P_{calc} for all 335 data points. Table 4-6 displays the effect that the $1.63t_2^{0.18}$ adjustment factor has on the entire dataset of all 335 tests. The original results are included for direct comparison.

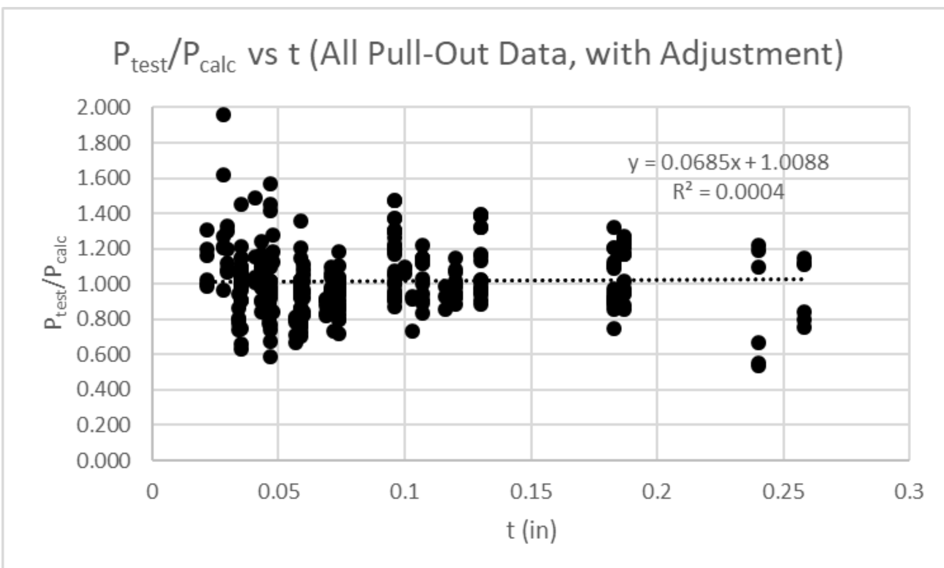

Figure 4.4 Effect of sheet thickness for all data with adjustment factor

Table 4-6 All Pull-Out Data with and without Adjustment Factor

	Original	Adjusted
n:	335	335
m:	334	334
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.038	1.015
βo (LRFD):	3.5	3.5
βo (LSD):	4.0	4.0
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.009	1.009
V_p:	0.218	0.180
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.038	1.015
Standard Deviation:	0.218	0.182
Coefficient of Variation:	0.210	0.180
Φ (LRFD):	0.548	0.572
Ω (ASD):	2.918	2.799
Alt Ω:	2.797	2.682
Φ (LSD):	0.434	0.457

With the $1.63t_2^{0.18}$ adjustment factor multiplied in, the pull-out strength equation is now accurate for any ratio of d/t, although in practice this ratio is usually in the range of 2 to 7. The accuracy of the new equation over all ratios of d/t is illustrated in Figure 4.5.

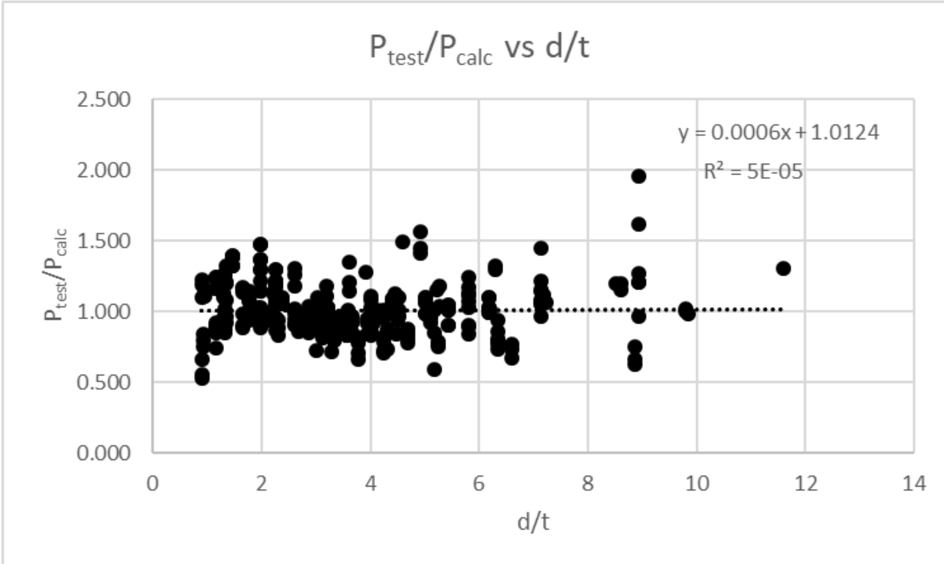

Figure 4.5 P_{test}/P_{calc} (with adjustment factor) versus d/t

<u>Section 4.4.2 – Effect of Adjustment on Various Thickness Ranges</u>

To confirm that the adjustment factor of $1.63t_2^{0.18}$ improves the standard pull-out strength equation across all reasonable ranges of sheet thickness, all pull-out data was divided into three thickness ranges: $t \leq 0.05$ inches, 0.05 inches $< t <$ 0.09 inches, and $t \geq 0.09$ inches. Additionally, the data was also broken down into the two thickness ranges of $t < 0.09$ inches and $t \geq 0.09$ inches. For direct comparison, the statistics for these ranges are detailed in the tables below both with and without the adjustment factor.

Table 4-7 Effect of Adjustment Factor When t $\leq$ 0.05 inches

	Original	Adjusted
n:	101	101
m:	100	100
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	0.943	1.045
βo (LRFD):	3.5	3.5
βo (LSD):	4.0	4.0
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.031	1.031
V_p:	0.197	0.204
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	0.943	1.045
Standard Deviation:	0.186	0.213
Coefficient of Variation:	0.197	0.204
Φ (LRFD):	0.510	0.556
Ω (ASD):	3.140	2.876
Alt Ω:	3.009	2.757
Φ (LSD):	0.405	0.441

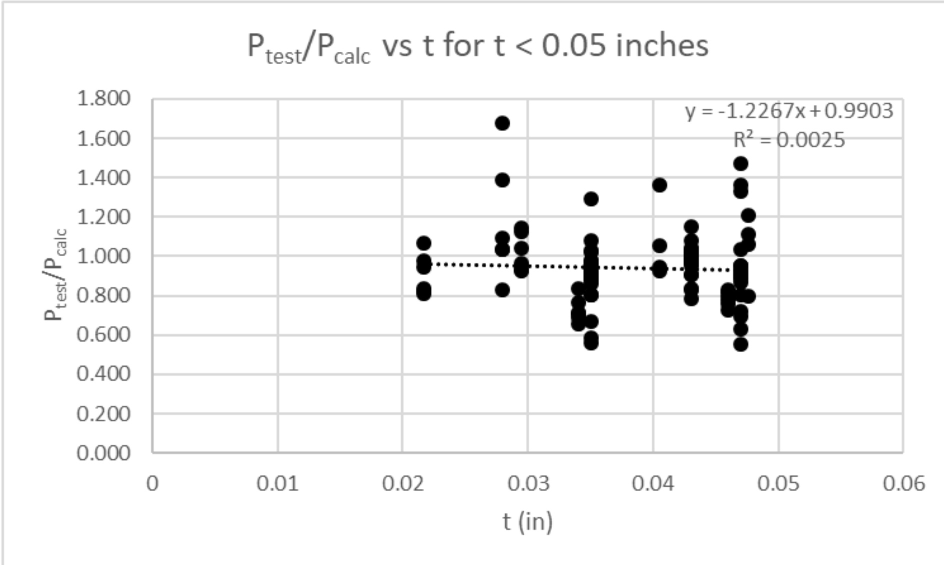

Figure 4.6 Original P_{test}/P_{calc} versus t for t ≤ 0.05 inches

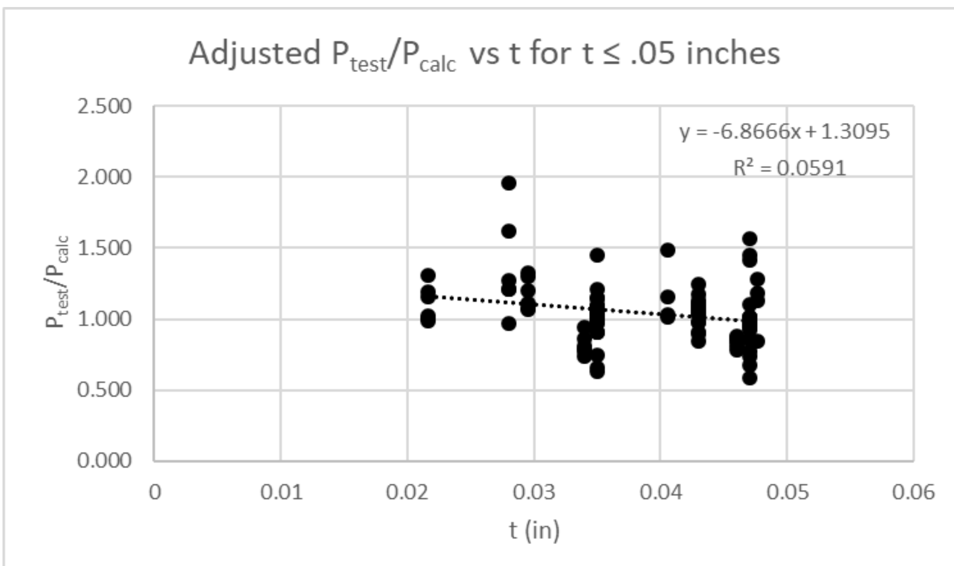

Figure 4.7 Adjusted P_{test}/P_{calc} versus t for t ≤ 0.05 inches

Table 4-8 Effect of Adjustment Factor When 0.05 inches < t < 0.09 inches

	Original	Adjusted
n:	103	103
m:	102	102
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	0.925	0.930
βo (LRFD):	3.5	3.5
βo (LSD):	4.0	4.0
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.030	1.030
V_p:	0.124	0.122
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	0.925	0.930
Standard Deviation:	0.114	0.114
Coefficient of Variation:	0.124	0.122
Φ (LRFD):	0.575	0.580
Ω (ASD):	2.781	2.759
Alt Ω:	2.665	2.644
Φ (LSD):	0.467	0.471

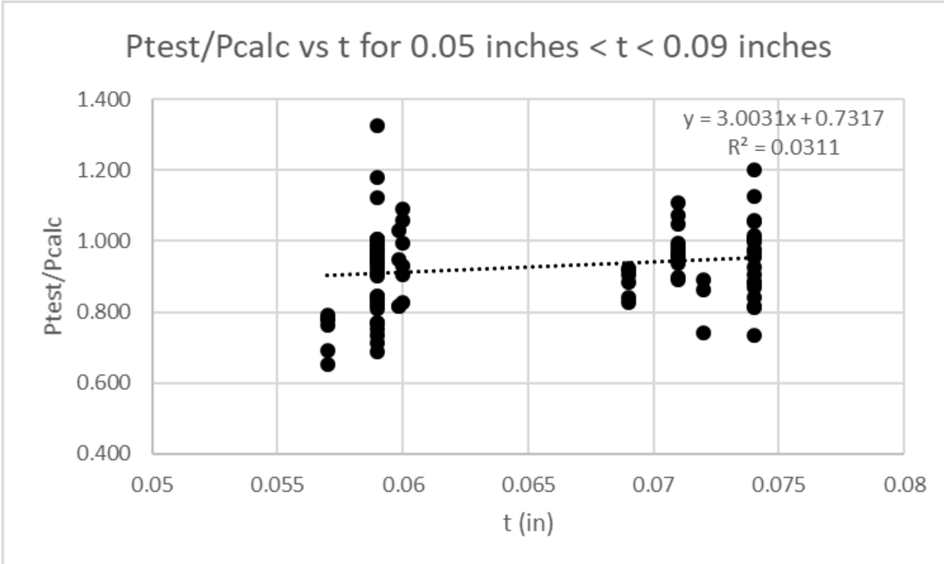

Figure 4.8 Original P_{test}/P_{calc} versus t for 0.05 inches < t < 0.09 inches

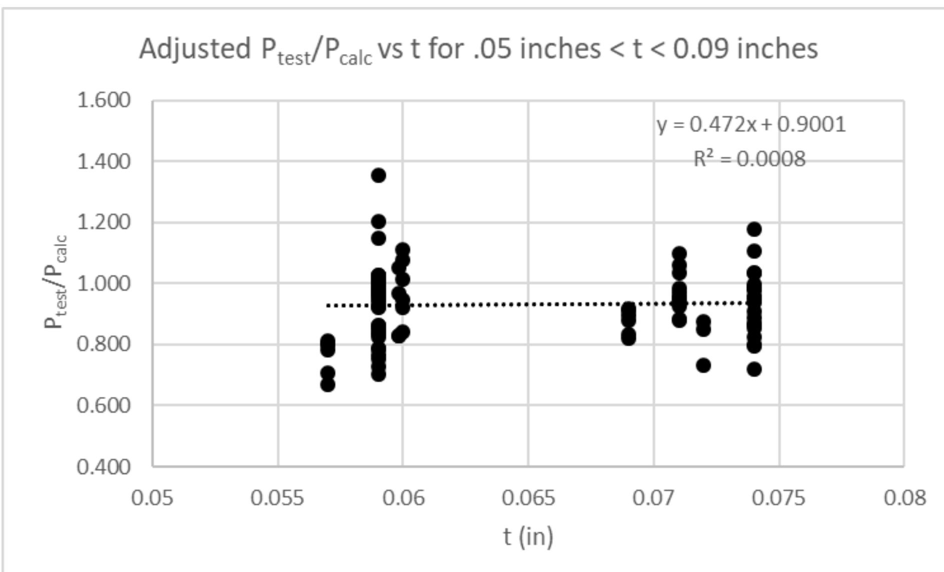

Figure 4.9 Adjusted P_{test}/P_{calc} versus t for 0.05 inches < t < 0.09 inches

Table 4-9 Effect of Adjustment Factor When $t \geq 0.09$ inches

	Original	Adjusted
n:	131	131
m:	130	130
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.200	1.058
βo (LRFD):	3.5	3.5
βo (LSD):	4.0	4.0
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.023	1.023
V_p:	0.169	0.169
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.200	1.058
Standard Deviation:	0.203	0.179
Coefficient of Variation:	0.169	0.169
Φ (LRFD):	0.689	0.607
Ω (ASD):	2.323	2.637
Alt Ω:	2.226	2.527
Φ (LSD):	0.552	0.487

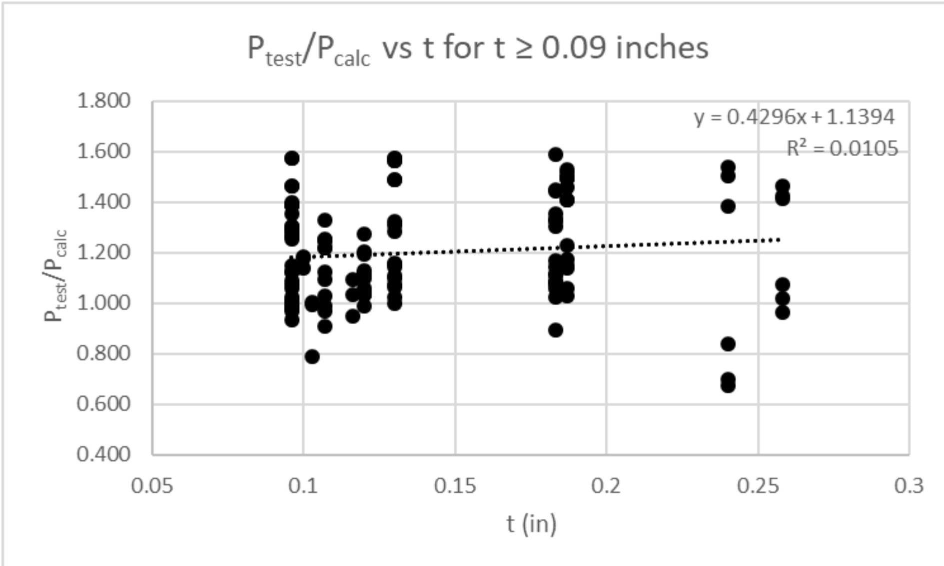

Figure 4.10 Original P_{test}/P_{calc} versus t for t ≥ 0.09 inches

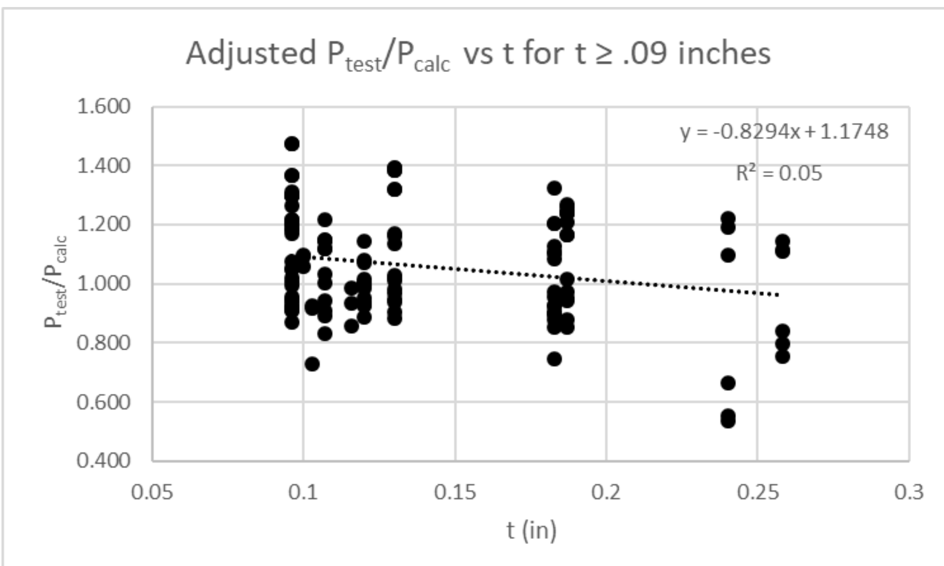

Figure 4.11 Adjusted P_{test}/P_{calc} versus t for t ≥ 0.09 inches

Table 4-10 Effect of Adjustment Factor When t < 0.09 inches

	Original	Adjusted
n:	204	204
m:	203	203
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	0.934	0.987
βo (LRFD):	3.5	3.5
βo (LSD):	4.0	4.0
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.015	1.015
V_p:	0.165	0.181
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	0.934	0.987
Standard Deviation:	0.154	0.179
Coefficient of Variation:	0.165	0.181
Φ (LRFD):	0.541	0.553
Ω (ASD):	2.956	2.892
Alt Ω:	2.833	2.772
Φ (LSD):	0.435	0.442

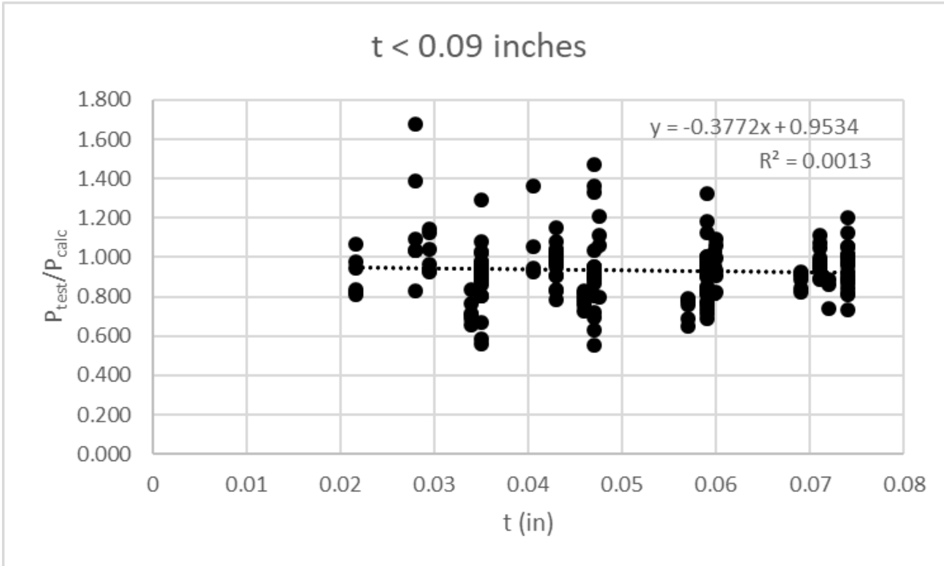

Figure 4.12 Original P_{test}/P_{calc} versus t for t < 0.09 inches

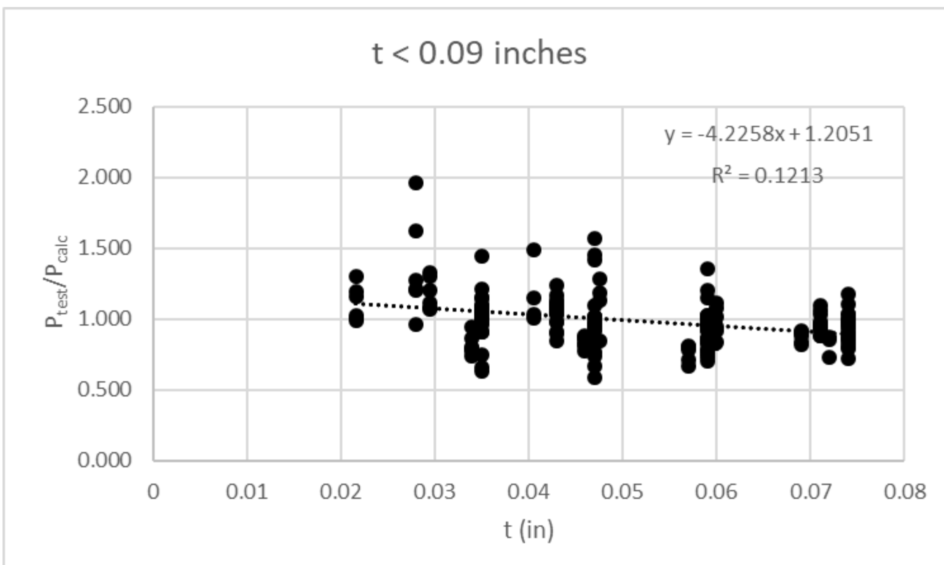

Figure 4.13 Adjusted P_{test}/P_{calc} versus t for t < 0.09 inches

The findings from this section indicate that, with the adjustment factor included, the value of Φ does not vary measurably based on sheet thickness. Because of this, it appears that a single Φ and Ω can be used for all thicknesses.

Section 4.4.3 – Effect of Adjustment on Ductile and Non-Ductile Tests

All 335 tests were divided into low-ductility and ductile connections to determine if ductility affected the accuracy of the standard equations. In practice, low-ductility connections are rarely designed in situations prone to pull-out. It is worth noting that the only low-ductility pull-out tests observed came from the Sivapathasundaram and Mahendran report, which did not conduct the AISI S905 standard pull-out test procedure, although the methods conducted were similar enough to be considered in this report. In total, 308 of the observed tests were determined to have used ductile steel, while the remaining 27 used low-ductility steel. As per AISI S100-16, Sections A3.1.2 and A3.1.3, low-ductility steels are defined as having a minimum elongation of less than 10%. In the following tables the statistics for ductile and low-ductility connections are separately displayed both with and without the adjustment factor of $1.63t_2^{0.18}$.

Table 4-11 Effect of Adjustment Factor on Ductile Connection Tests

	Original	Adjusted
n:	308	308
m:	307	307
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.038	1.006
βo (LRFD):	3.5	3.5
βo (LSD):	4.0	4.0
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.010	1.010
V_p:	0.211	0.180
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.038	1.006
Standard Deviation:	0.219	0.181
Coefficient of Variation:	0.211	0.180
Φ (LRFD):	0.546	0.565
Ω (ASD):	2.929	2.830
Alt Ω:	2.807	2.712
Φ (LSD):	0.433	0.586

Table 4-12 Effect of Adjustment Factor on Low-ductility Connection Tests

	Original	Adjusted
n:	27	27
m:	26	26
C_φ (LRFD):	1.52	1.52
C_φ (LSD):	1.42	1.42
M_m:	1.1	1.1
F_m:	1	1
P_m:	1.095	1.173
βo (LRFD):	3.5	3.5
βo (LSD):	4.0	4.0
V_M:	0.1	0.1
V_F:	0.1	0.1
C_p:	1.123	1.123
V_p:	0.207	0.123
V_Q:	0.21	0.21
Mean P_{test}/P_{calc}	1.095	1.173
Standard Deviation:	0.227	0.144
Coefficient of Variation:	0.207	0.123
Φ (LRFD):	0.566	0.724
Ω (ASD):	2.827	2.211
Alt Ω:	2.709	2.119
Φ (LSD):	0.447	0.586

For low-ductility connections, the adjustment factor leads to a higher adjusted Φ of over 0.70, however, due to the limited number of low-ductility tests additional research should be conducted before conclusions should be drawn.

Section 4.5 – Overall Impressions and Recommendations

1. For the limit state of pull-out, the test data indicates that the current nominal strength prediction equation in AISI S100-16 needs to be revised. Based on analysis of the available data, an adjustment factor of $1.63t_2^{0.18}$ is proposed to be multiplied into the existing equation, resulting in a new nominal pull-over strength prediction equation of $P_n = 0.85t_2dF_u(1.63t_2^{0.18})$.

2. For the limit state of pull-out, analysis of the entire data set, and of individual conditions, suggests that the resistance factor for both LRFD and LSD could be increased by 0.05 to 0.55 and 0.45 respectively, and that the ASD factor of safety could be decreased to 2.80, assuming the recommended adjustment factor of $1.63t_2^{0.18}$ is incorporated into the nominal pull-over strength prediction equation.

3. For screws loaded in pull-out, the alternate factor of safety using the live to dead load ratio of 5:1 which is the basis of the rest of the AISI S100-16, should be strongly considered.

4. Table 4-13 and Figure 4.14 show how the adjustment factor affects P_n and ΦP_n. When the thickness t_2 is greater than 0.05 inches, the usable strength ΦP_n is higher with the proposed adjustment factor.

Table 4-13 Effect of Proposed Adjustment Factor upon Pull-Out Strength

t_2	$\frac{\text{Proposed Pn}}{\text{2016 Pn}}$	$\frac{Proposed\ \Phi Pn}{2016\ \Phi Pn}$
0.01	0.71	0.78
0.02	0.81	0.89
0.03	0.87	0.95
0.04	0.91	1.00
0.05	0.95	1.05
0.06	0.98	1.08
0.07	1.01	1.11
0.08	1.03	1.14
0.09	1.06	1.16
0.10	1.08	1.18

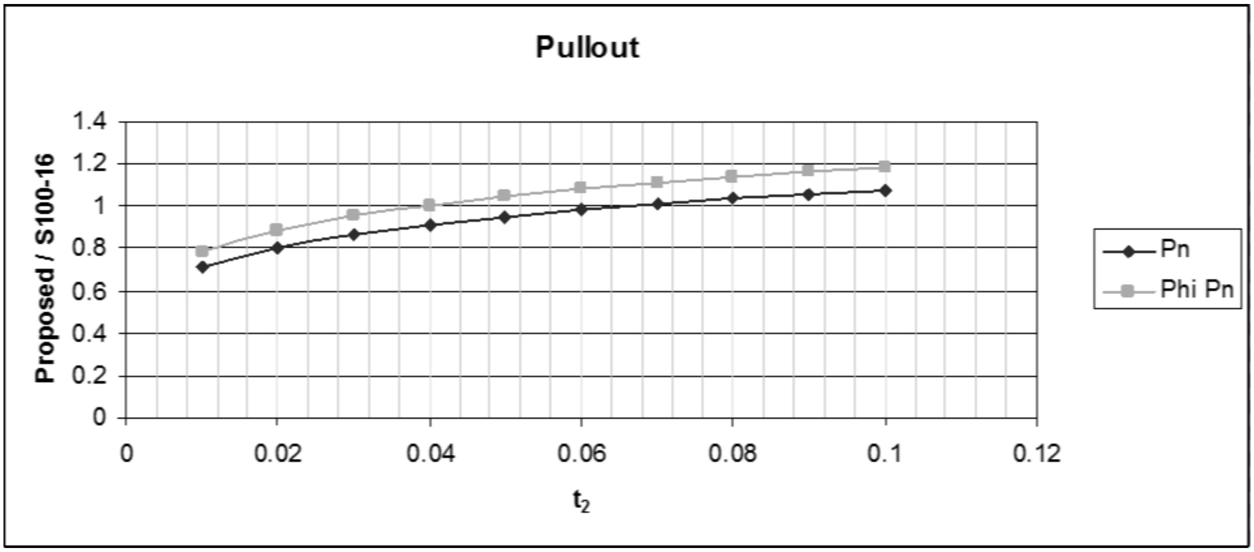

Figure 4.14 Effect of proposed adjustment factor upon pull-out strength

Chapter 5 – Summary

In total, this report analyzed the results of 702 shear tests, 143 pull-over tests, and 335 pull-out tests of steel-to-steel screwed connections. This analysis allowed the current AISI S100 Standard provisions for steel-to-steel screw connections loaded in shear and tension (but not combined actions) to be evaluated.

From this evaluation, the following changes are recommended:

Shear:

No changes to nominal strength equations.

Table 5-1: Proposed Revisions to Resistance Factors and Factor of Safety for Shear

Revised Resistance Factor and Factor of Safety	S100-16	Proposed for S100-20
Φ (LRFD)	0.50	0.55
Ω (ASD)	3.00	2.80
Φ (LSD)	0.40	0.45

Pull-Over:

OPTION 1: No changes to nominal strength equations.

Table 5-2: Proposed Revisions to Resistance Factors and Factor of Safety for Pull-Over (Option 1)

Revised Resistance Factor and Factor of Safety	S100-16	Proposed for S100-22 Ductile Steel And Low-ductility Steel with $t_1 \geq 0.023$ inches	Proposed for S100-22 Low-ductility Steel (< 10%) with $t_1 < 0.023$ inches
Φ (LRFD)	0.50	0.55	0.30
Ω (ASD)	3.00	2.90	4.85
Φ (LSD)	0.40	0.40	0.20

OPTION 2: Change the nominal strength equation for thin, low-ductility sheet

$$P_{nov} = 1.5t_1d'_wF_{u1}$$

Except for low-ductility sheet with a thickness less than 0.023 inches, where:

$$P_{nov} = 0.90t_1d'_wF_{u1}$$

Table 5-3: Proposed Revisions to Resistance Factors and Factor of Safety for Pull-Over (Option 2)

Revised Resistance Factor and Factor of Safety	S100-16	Proposed for S100-22
Φ (LRFD)	0.50	0.55
Ω (ASD)	3.00	2.90
Φ (LSD)	0.40	0.40

<u>Pull-Out:</u>

Modify the nominal strength equations by adding an adjustment factor, $(1.63t_2^{0.18})$.

$$P_n = 0.85t_2dF_u(1.63t_2^{0.18})$$

Table 5-4: Proposed Revisions to Resistance Factors and Factor of Safety for Pull-Out

Revised Resistance Factor and Factor of Safety	S100-16	Proposed for S100-22
Φ (LRFD)	0.50	0.55
Ω (ASD)	3.00	2.80
Φ (LSD)	0.40	0.45

Appendix

All data considered in this study is available as Microsoft Excel files.

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