

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

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

By

THOMAS STEVENS
UNIVERSITY OF FLORIDA UNDERGRADUATE
RESEARCH ASSISTANT

THOMAS SPUTO, PH.D., P.E., S.E., SECB
INDUSTRY ADVISOR

JENNIFER BRIDGE, PH.D.
ACADEMIC ADVISOR

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UNIVERSITY OF FLORIDA
GAINESVILLE, FLORIDA

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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List of Variables

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

β_o = 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

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

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

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

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

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

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

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). “Tek’s 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
β_o (LRFD):	3.5	3.5
β_o (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

Section 2.2.2 - 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
β_o (LRFD):	3.5	3.5
β_o (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

Section 2.2.3 - 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
β_o (LRFD):	3.5	3.5
β_o (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 $P_{\text{test}}/P_{\text{calc}}$ in the t_2/t_1 range between 0.75 to 2.25. This will be discussed further in Section 2.4.2.

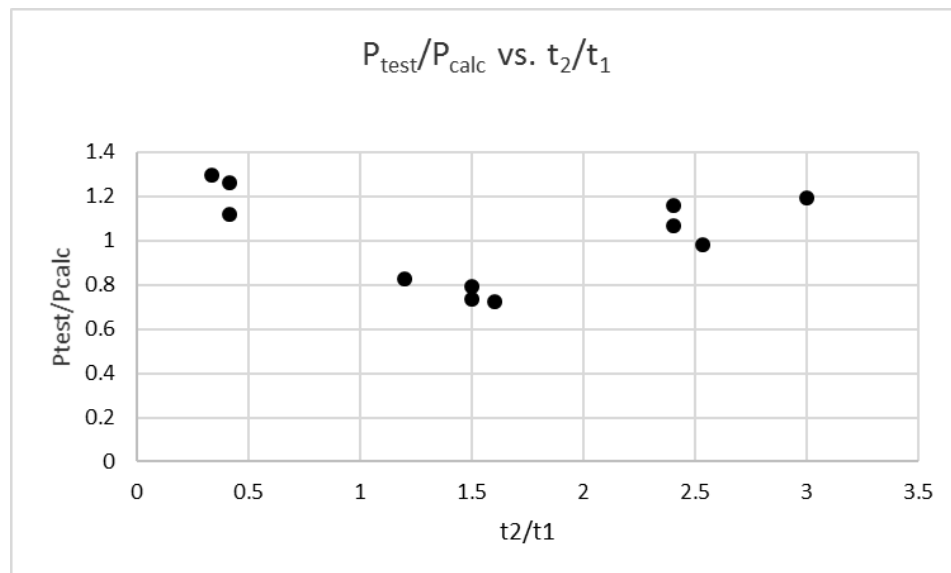


Figure 2.1 Ratio of tested strength to calculated strength versus ratio of bottom sheet thickness to top sheet thickness for the Huynh, Pram, and Hancock (2018)

Section 2.2.4 - 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
β_o (LRFD):	3.5	3.5
β_o (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

Section 2.2.5 - 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
β_o (LRFD):	3.5	3.5
β_o (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

Section 2.2.6 - 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
β_o (LRFD):	3.5	3.5
β_o (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

Section 2.2.7 - 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
β_o (LRFD):	3.5	3.5
β_o (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
β_o (LRFD):	3.5	3.5
β_o (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
β_o (LRFD):	3.5	3.5
β_o (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