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Strength of Steel-to-Steel Screw Connections - Update to Provisions

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Abstract

The objective of this research was to review the existing provisions of the AISI S100-16 *North American Specification for Cold-Formed Steel Structural Members* [1], for screw connections loaded in shear and tension (but not combined actions).

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 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.

1. Introduction

The existing provisions for screw connections in the American Iron and Steel Institute (AISI) S100-16 Standard [1] are based on European testing on steels and fasteners which may not reflect those found in the North American market [2]. 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 [3] presented potential unconservative predictions, specifically for screw pull-over for thinner sheets and/or lower ductility steels. A 1996 study by Kreiner [4] also found possible unconservative pull-over results. This study aimed to review the current screw provisions in the AISI S100 Standard, with the potential of revising existing strength equations, resistance factors, and factors of safety. The failure modes analyzed in this study were shear (tilting and bearing), pull-out, and pull-over. Failure of the screw itself was 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 examined 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 was compared to the calculated strength according to

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the AISI S100 to determine the viability of the current provisions.

Phase 2 of this study examined 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 included the results for 143 connections which failed by pullover and 335 connections which failed by pullout.

Within this study, the ductility of the steel was considered for some limit states. For the purpose of this study, "ductile" steel was 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 was 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% .

2. Screws Loaded in Shear

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 [5]. The reader is referred to that paper for additional information.

2.2 Current Provisions and Parameters

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 $t_2/t_1 \le 1.0$, 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 $t_2/t_1 \ge 2.5$, P_{nv} shall be taken as the smaller of

$P_{nv} = 2.7 t_1 d F_{u1}$ AISI S100-16 Eq. J4.3.1-4

$P_{nv} = 2.7 t_2 d F_{u2}$ 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 study, 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.

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 1.

Table 1. 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

2.4 Further Analysis of Shear Data

The data was further divided to study the effects of specific parameters, including:

1. Effect of single versus multiple screws
2. Ductile versus low-ductility steel
3. Thin versus thick sheets
4. Ratio of sheet thickness

The effect of these parameters are reported on in the project report [6] in further detail.

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.

3 Pull-over

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 phase the 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.

3.2 Current Provisions and Parameters

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 calculation:

$$P_{nov} = 1.5 t_1 d'_w F_{u1} \qquad \text{AISI S100-16 Eq. J4.4.2-1}$$

Where:

d'_w = Effective pull-over diameter

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 study, 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.

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 2.

Table 2. 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

3.4 Further Analysis of Pull-Over Data

The data was further divided to study the effects of specific parameters, including:

1. Ductile versus low-ductility steel
2. Sheet thickness versus ductility

The effect of these parameters are reported on in the project report [6] in further detail.

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 [4] should be seriously considered for inclusion in the AISI S100 Standard.

4 Screw Pull-Out

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.

4.2 Current Provisions and Parameters

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 study, 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.

4.3 Total Pull-Out Database

In total, 335 tests from 4 different sources were considered and shown in Table 3. 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.

4.4 Further Analysis of Pull-Out Data

The data was further divided to study the effects of specific parameters, including:

1. Ductile versus low-ductility steel
2. Sheet thickness versus ductility

As shown in Figure 1, P_{test}/P_{calc} values tend to increase as sheet thickness increases. Figure 2, 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.

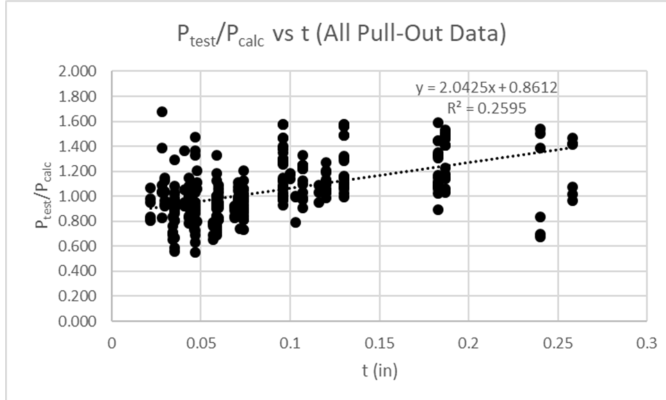

Figure 1 Effect of thickness for all data

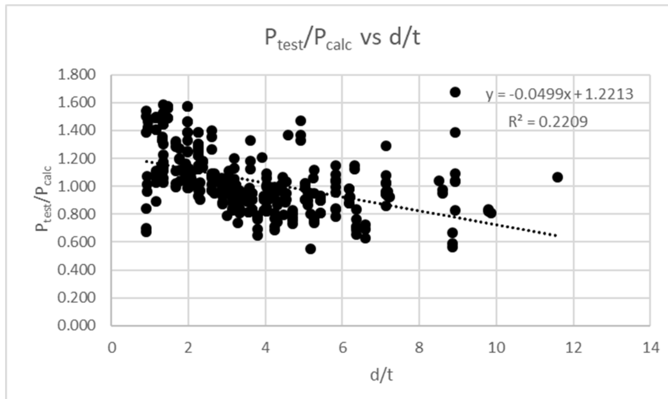

Figure 2 P_{test}/P_{calc} versus d/t

The effect of these parameters are reported on in the project report [6] in further detail.

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 $P_n = 0.85t_2dF_u(1.63t_2^{0.18})$. The results are illustrated in Figure 3.

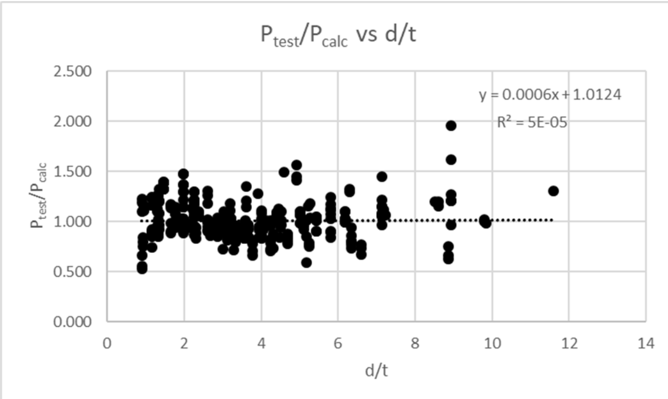

Figure 3. P_{test}/P_{calc} (with adjustment factor) versus d/t

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. When the thickness t_2 is greater than 0.05 inches, the usable strength ΦP_n is higher with the proposed adjustment factor.

Table 3. 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

5. Conclusions

In total, this study 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, with changes to resistance and safety factors as shown in Table 4.

Table 4 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, with changes to resistance and safety factors as shown in Table 5.

Table 5 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

$$P_{nov} = 1.5 t_1 d'_w F_{u1}$$

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

$$P_{nov} = 0.90 t_1 d'_w F_{u1}$$

Table 6: 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

Pull-Out:

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

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

Table 7: 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

6. Acknowledgments

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References

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