International Specialty Conference on Cold-Formed Steel Structures

(2010) - 20th International Specialty Conference on Cold-Formed Steel Structures

Nov 3rd

Cold Formed Steel Tension Members with Two and Three Staggered Bolts

D. M. Fox

R. M. Schuster

Recommended Citation

Fox, D. M. and Schuster, R. M., "Cold Formed Steel Tension Members with Two and Three Staggered Bolts" (2010). *International Specialty Conference on Cold-Formed Steel Structures*. 4.
http://scholarsmine.mst.edu/isccss/20iccfss/20iccfss-session11/4

Twentieth International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, U.S.A., November 3 & 4, 2010

Cold Formed Steel Tension Members with Two and Three Staggered Bolts

D.M. Fox[1] and R.M. Schuster[2]

Abstract

The second edition of the North American Specification for the Design of Cold Formed Steel Structural Members was published in October of 2007 for use in Canada, Mexico, and the United States. This Specification contains two country specific appendices, namely Appendix A (ANSI/AISI S100-07) for use in the US and Mexico and Appendix B (CSA S136-07) for use in Canada. Both Appendix A and B require that a bolt stagger reduction factor of 0.90 be used when calculating the tearing failure strength [resistance] of a cold formed steel member in tension with staggered bolts. This 10% reduction was based on limited testing that was carried out by Dr. Roger LaBoube of the University of Missouri-Rolla, which has now changed its name to the "Missouri University of Science & Technology".

The objective of this study was to establish if this bolt stagger reduction factor is indeed necessary since the stagger term of [$s^2/4g$] has been used in the steel industry for many years without such a reduction. Experimental testing of two and three staggered bolt tension members was carried out in the Structures Laboratory of the Department of Civil Engineering at the University of Waterloo. Based on the test results of the 1.6 mm, 2.1 mm, 2.9 mm, 4 mm, 5 mm, and 6 mm thick steel sheet, it can be concluded that the 0.90 bolt stagger reduction factor is not necessary for the steel plate thicknesses tested.

---

[1] Engineering Manager, iSPAN Systems, Richmond Hill, Ontario, Canada
[2] Professor Emeritus of Structural Engineering and Director of the Canadian Cold Formed Steel Research Group, Department of Civil Engineering, University of Waterloo, Waterloo, Canada

Introduction

The North American Specification for the Design of Cold Formed Steel Structural Members [1] (herein referred to as the NAS) applies for use in Canada, Mexico, and the United States. This Specification contains two country-specific appendices, namely Appendix A for use in the US and Mexico and Appendix B for use in Canada. Both Appendix A and B require that a bolt stagger reduction factor of 0.9 be used when calculating the nominal tensile resistance at the net section. This 10% reduction factor was based on limited testing that was carried out by Dr. Roger LaBoube at the University of Missouri-Rolla.

The validity of this reduction factor was first brought into question by a Canadian structural engineer who was designing cold formed steel tension members that had the same thickness as hot rolled steel tension members. In the Canadian hot rolled steel standard *"Design of Steel Structures"* (CAN/CSA-S16-09) [2] the procedure for determining the tensile resistance of staggered bolted tension members does not contain a reduction factor, regardless of thickness of the steel plate material. To investigate this difference in design methods, a study was initially carried out at the University of Waterloo by Toutounchian et al [3] using two bolts with two different stagger patterns and six different steel plate thicknesses. A follow-up study was carried out by Farashah [4] to complete the testing of the two-bolt study by Toutounchian et al [3] and to also include three-bolt staggered tension members.

The objective of this work was to analyse the two-bolt and three-bolt staggered test results to establish if the 0.90 reduction factor is required when designing tension member connections with staggered bolt patterns.

Current Design Approaches

<u>Appendix A Method</u>

The method in Appendix A of NAS-07 [1], which applies to the US and Mexico, for calculating the nominal tensile strength of a member for failure due to rupture of the net section involving stagger is:

$$P_n = A_n F_t \qquad \textit{Eq. E3.2-6}$$

$$A_n = C_r\,[A_g - n_b\, d_h\, t + (\sum s'^2/4g)t] \qquad \textit{Eq. E3.2-7}$$

Where,

F_t = Nominal tensile stress in flat sheet; in accordance with Eqs. E3.2-2 to E3.2-5 of the NAS [1]

C_r = Bolt stagger reduction factor = 0.90
s = Sheet width divided by number of bolt holes in cross section being analyzed
F_u = Tensile stress of material
d = Nominal bolt diameter
A_n = Net area of the connected part
A_g = Gross area of member
t = Material thickness
s’ = Longitudinal center-to-center spacing of any two consecutive holes
g = Transverse center-to-center spacing between fastener gauge lines
n_b = Number of bolt holes in cross section being analyzed
d_h = Diameter of a standard hole
h = Bolt hole diameter (mm), (bolt diameter + 1/16 in. (1.59 mm))

Appendix B Method

The method in Appendix B of NAS-07 [1], which applies to Canada, for calculating the nominal tensile resistance of a member for failure due to rupture of the net section involving stagger is:

$T_n = A_n F_u$ *Eq. C2.2-1*

$A_n = L_c t$ *Eq. C2.2-2*

$L_c = C_r L_s$ *Eq. C2.2-4*

Where,
A_n = Critical *net area* of connected part (mm^2)
F_u = Tensile strength of steel (MPa)
L_c = Summation of critical path lengths of each segment along a potential failure path of minimum strength (mm)
t = Material thickness (mm)
C_r = Bolt stagger reduction factor = 0.90
L_s = Net failure path length inclined to force [including ($s^2/4g$) allowance for staggered holes] (mm)
s = Pitch, fastener spacing parallel to force (mm)
g = Gauge, fastener spacing perpendicular to force (mm)
w = Specimen width (mm)
h = Bolt hole diameter (mm), (bolt diameter + 1 mm (0.0394 in.)

Test Program

Shown in Table 1 and Table 2 are the thicknesses and dimensions of the steel sheets that were provided by ArcelorMittal. Six steel sheet thicknesses were chosen for the two-bolt plates and five thicknesses were chosen for the three-bolt plates; steel sheet thicknesses ranged from approximately 1.6 mm [0.06in] to 6 mm [0.25in]. All specimens were prepared by Baumeier Corporation in Waterloo, Ontario. Specimens were laser cut resulting in consistent workmanship with precise plate dimensions and hole patterns. All specimen dimensions were selected in order to ensure that fracture of the net section was the governing failure mode and that other modes, such as bearing failure, would not occur.

The test specimens were fabricated as rectangular plates with a constant length of 200 mm for the two-bolt plates and a constant length of 240 mm for the three-bolt plates. Single shear and double shear connections were tested. For double shear connections where specimens were designated as having the outside sheets controlling, the inside sheet thickness was selected in order to ensure failure in the outside sheets. Where specimens were designated as having the inside sheet controlling, the outside sheets of the double shear connection were selected in order to ensure failure in the inside sheet.

Shown in Figure 1 and Figure 2 are schematic diagrams of the two-bolt and three-bolt specimens, respectively. For the case of three-bolt connections, two different bolt stagger orientations were tested as shown in Figure 2(a) and Figure 2(b). The ultimate tensile stress, F_u, of the specimens were obtained from coupon tests that were carried out at the University of Waterloo; results of the coupon tests can be found in Table 1 and Table 2.

All tests were carried out in the Structures Laboratory of the Department of Civil Engineering at the University of Waterloo, the results of which are summarized in Table 3 through Table 7. Shown in Figure 3 is a photograph of the test frame that was used with all specimens which were loaded quasi-statically until failure. Typical failure in both two-bolt and three-bolt specimens occurred as fracture of the net section along the bolt holes as shown in Figure 4. The failure load was recorded for each specimen, a summary of which is included in Table 3 through Table 7.

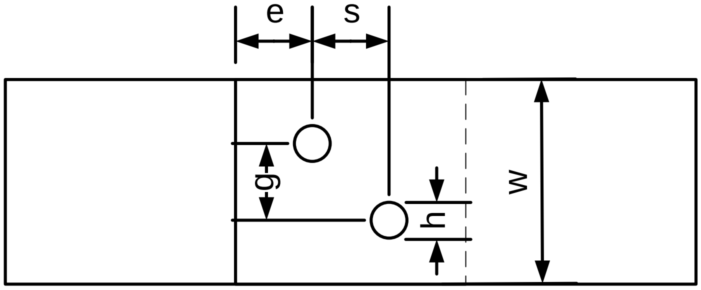
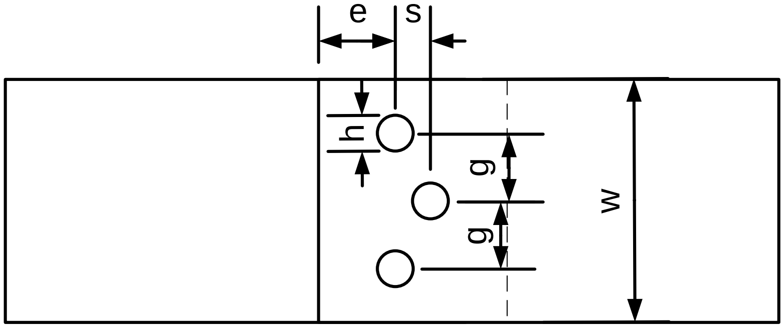
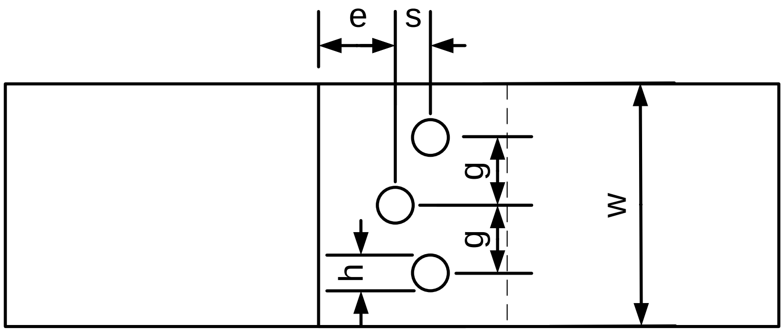


Figure 1 Schematic Diagram of Two-Bolt Specimens



(a) With Stagger Pattern 1



(b) With Stagger Pattern 2

Figure 2 Schematic Diagram of Three-Bolt Specimens

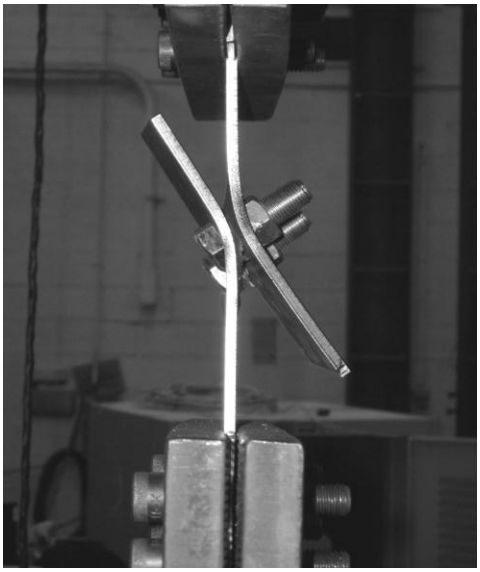
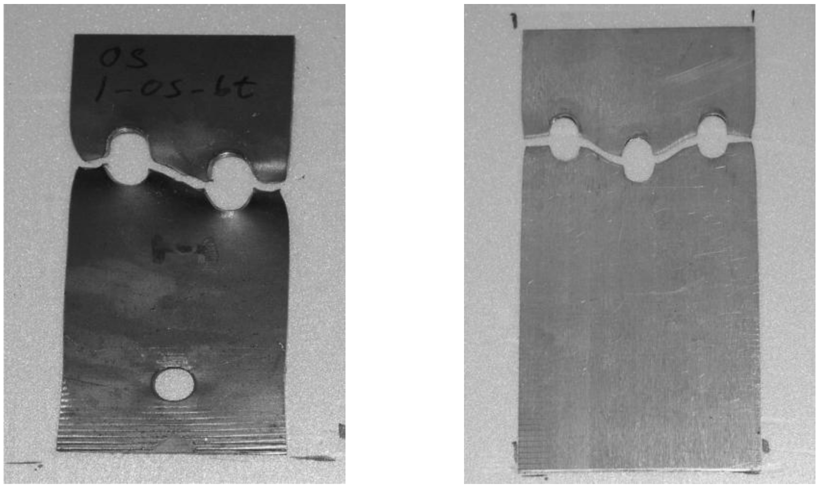


Figure 3 Photograph of Test Specimen in Tensile Test Machine



(a) Two-bolt Specimen Failure (b) Three-bolt Specimen Failure

Figure 4 Photograph of Typical Observed Failure Modes

Analysis of Test Results

In order to ascertain whether a reduction factor is required for staggered bolts, the predicted nominal strength [resistance] was calculated without the reduction factor as follows:

$$T_{n,\,NR} = A_n F_u \qquad \textit{Eq. 1}$$

$$A_{n,\,NR} = L_c\, t \qquad \textit{Eq. 2}$$

$$L_{c,\,NR} = L_s \qquad \textit{Eq. 3}$$

Where,

$A_{n,\,NR}$ = Critical *net area* of connected part without a reduction factor for staggered bolts (mm^2)

F_u = Tensile strength of steel (MPa)

$L_{c,\,NR}$ = Summation of critical path lengths of each segment along a potential failure path of minimum strength without a reduction factor for staggered bolts (mm)

L_s = Net failure path length inclined to force [including ($s^2/4g$) allowance for staggered holes] (mm)

s = Pitch, fastener spacing parallel to force (mm)

g = Gauge, fastener spacing perpendicular to force (mm)

Since the specimens were fabricated such that fracture of the net section was the controlling failure mode, only fracture of the net section was considered in the calculations with the allowance for staggered holes. The results of the calculations for each test specimen are included in Table 3 through Table 7. Also included is the ratio of tested strength [resistance] to predicted nominal strength [resistance] for each test specimen.

A reduction factor would be required if, on average, specimens tended to have the ratio of tested strength to predicted nominal strength below 1.0. As shown in Table 3 through Table 7, the average ratio ranged from 1.09 to 1.11. Further, the standard deviation ranged from 0.03 to 0.11, meaning that the most of the test specimens' predicted nominal strength [resistance], calculated by Eq. 1 without a hole stagger reduction factor, proved to be accurate or conservative. This can also be observed from Figure 5 and Figure 6. Since the large majority of the test to calculated strength [resistance] ratios are above the ideal line of 1.0, it can be stated that a reduction factor is not required in order to accurately predict the nominal strength [resistance] of tension members with staggered bolt holes for the steel thicknesses tested.

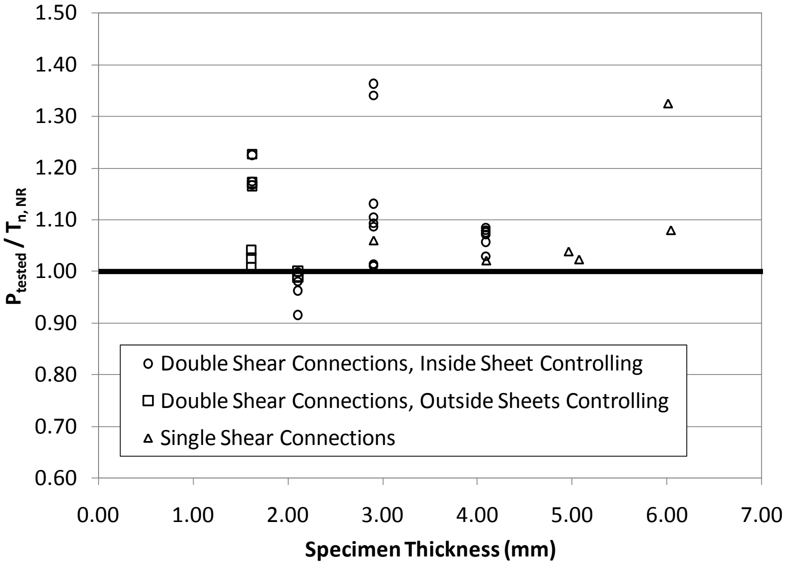


Figure 5 Tested strength to predicted nominal strength of two-bolt specimens

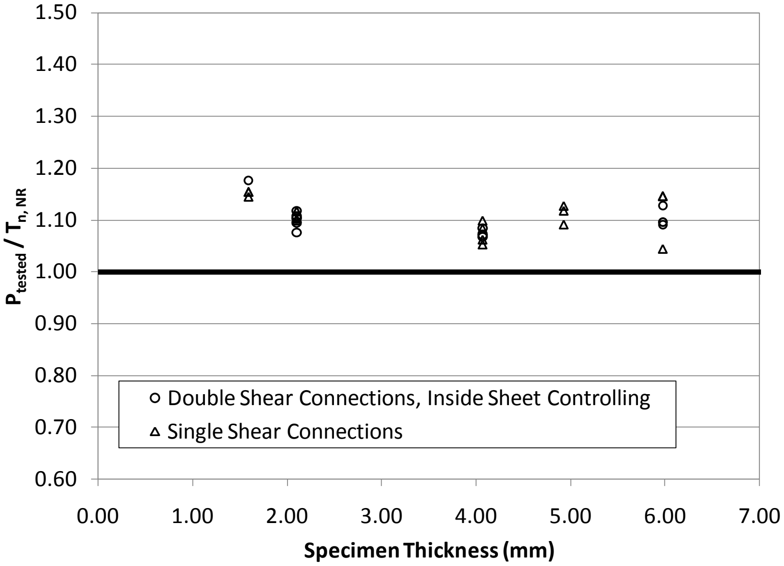


Figure 6 Tested strength to predicted nominal strength of three-bolt specimens

Summary

Presented in this paper is a study conducted at the University of Waterloo in order to ascertain the need for a reduction factor currently included in the NAS [1] for staggered bolted connections. An experimental test program was conducted to collect data to either substantiate the need for or the possible elimination of the reduction factor.

Based on the test results, it was shown that the majority of the tested connection strengths are conservatively predicted using the current NAS [1] equations without the staggered bolt hole reduction factor for the steel thicknesses tested. As such, it is recommended that consideration be given to remove the reduction factor from both Appendix A and Appendix B of the NAS [1], which would bring tension members in line with provisions contained in other current steel design standards.

References

[1] AISI (2007). North American Specification for the Design of Cold-Formed Steel Structural Members. American Iron and Steel Institute: Washington, D.C.

[2] CSA (2009). CAN/CSA-S16-09: Design of Steel Structures. Canadian Standards Association: Toronto, ON

[3] Toutounchian, A., Canete, D., Mazhar, S., and Guermon, T. (2007). Cold Formed Steel Tension Member Connections with Staggered Bolts. 4th Year Civil Engineering Project, Department of Civil Engineering, University of Waterloo: Waterloo, ON

[4] Farashah, M. (2009). Cold Formed Steel Tension Member Connections with Two and Three Staggered Bolts. Co-operative Education Report, Department of Civil Engineering, University of Waterloo: Waterloo, ON

Table 1 Mechanical Properties of Sheet Steel used in 2 Bolt Specimens

Material ID	t (mm)	F_y (MPa)	F_u (MPa)	% Elong
2B-1.6	1.62	n/a	372	41%
2B-1.6-S1-O	1.61	n/a	427	33%
2B-2.1	2.10	n/a	462	33%
2B-2.1-S1-O	2.11	n/a	469	31%
2B-2.9	2.90	n/a	347	45%
2B-4.0	4.09	n/a	555	31%
2B-5.0-S0.5	4.96	n/a	649	28%
2B-5.0-S0/S1	5.07	n/a	624	28%
2B-6.0-S0/S0.5	6.01	n/a	322	46%
2B-6.0-S1	6.04	n/a	373	47%

Table 2 Mechanical Properties of Sheet Steel used in 3 Bolt Specimens

Material ID	t (mm)	F_y (MPa)	F_u (MPa)	% Elong
3B-1.6	1.59	378	422	34%
3B-2.1	2.10	376	447	32%
3B-4	4.07	602	675	25%
3B-5	4.93	512	609	20%
3B-6	5.98	287	375	41%

Table 3 Summary of Test Results, 2 Bolt Tests, Single Shear Connections

Specimen ID	t (mm)	F_u (MPa)	d (mm)	w (mm)	s (mm)	g (mm)	h (mm)	P_{tested} (kN)	$T_{n, NR}$ (kN)	$\frac{P_{tested}}{T_{n, NR}}$
O-2.9t-0.5S-1	2.90	347	12.7	75.0	12.7	35.0	13.7	52.0	49.1	1.06
O-4t-0.5S-1	4.09	555	12.7	75.0	12.7	35.0	13.7	113	111	1.02
O-5t-0.5S-1	4.96	649	12.7	75.0	12.7	35.0	13.7	163	157	1.04
O-5t-1.0S-1	5.07	624	12.7	75.0	25.4	35.0	13.7	169	165	1.02
O-6t-0.5S-1	6.01	322	12.7	75.0	12.7	35.0	13.7	125	94	1.32
O-6t-1.0S-1	6.04	373	12.7	75.0	25.4	35.0	13.7	127	118	1.08
									Average	1.10
									Standard Deviation	0.11

Table 4 Summary of Test Results, 2 Bolt Tests, Double Shear Connections, Outside Sheets Controlling

Specimen ID	t (mm)	F_u (MPa)	d (mm)	w (mm)	s (mm)	g (mm)	h (mm)	P_{tested} (kN)	$T_{n, NR}$ (kN)	$\frac{P_{tested}}{T_{n, NR}}$
O - 1.6 t - 0.5 S - 1	1.62	372	12.7	75.0	12.7	35.0	13.7	72.1	58.8	1.23
O - 1.6 t - 0.5 S - 2	1.62	372	12.7	75.0	12.7	35.0	13.7	68.9	58.8	1.17
O - 1.6 t - 0.5 S - 3	1.62	372	12.7	75.0	12.7	35.0	13.7	68.5	58.8	1.17
O - 1.6 t - 1 S - 1	1.61	427	12.7	75.0	25.5	35.0	13.7	74.8	71.8	1.04
O - 1.6 t - 1 S - 2	1.61	427	12.7	75.0	25.5	35.0	13.7	72.4	71.8	1.01
O - 1.6 t - 1 S - 3	1.61	427	12.7	75.0	25.5	35.0	13.7	73.7	71.8	1.03
O - 2.1 t - 0.5 S - 1	2.10	462	12.7	75.0	12.7	35.0	13.7	93.5	94.6	0.99
O - 2.1 t - 0.5 S - 2	2.10	462	12.7	75.0	12.7	35.0	13.7	93.7	94.6	0.99
O - 2.1 t - 0.5 S - 3	2.10	462	12.7	75.0	12.7	35.0	13.7	94.7	94.6	1.00
									Average	1.09
									Standard Deviation	0.11

Table 5 Summary of Test Results, 2 Bolt Tests, Double Shear Connections, Inside Sheet Controlling

Specimen ID	t (mm)	F_u (MPa)	d (mm)	w (mm)	s (mm)	g (mm)	h (mm)	P_{tested} (kN)	$T_{n, NR}$ (kN)	P_{tested} ---------- $T_{n, NR}$
I - 1.6 t - 0.5 S - 1	1.62	372	12.7	75.0	12.7	35.0	13.7	36.0	29.4	1.23
I - 1.6 t - 0.5 S - 2	1.62	372	12.7	75.0	12.7	35.0	13.7	34.5	29.4	1.17
I - 1.6 t - 0.5 S - 3	1.62	372	12.7	75.0	12.7	35.0	13.7	34.3	29.4	1.17
I - 2.1 t - 0.5 S - 2	2.10	462	12.7	75.0	12.7	35.0	13.7	43.3	47.3	0.92
I - 2.1 t - 0.5 S - 3	2.10	462	12.7	75.0	12.7	35.0	13.7	47.2	47.3	1.00
I - 2.1 t - 1 S - 2	2.10	462	12.7	75.0	25.5	35.0	13.7	48.8	50.7	0.96
I - 2.1 t - 1 S - 3	2.10	462	12.7	75.0	25.5	35.0	13.7	49.7	50.7	0.98
I - 2.9 t - 0.5 S - 1	2.90	347	12.7	75.0	12.7	35.0	13.7	49.6	49.1	1.01
I - 2.9 t - 0.5 S - 2	2.90	347	12.7	75.0	12.7	35.0	13.7	55.5	49.1	1.13
I - 2.9 t - 0.5 S - 3	2.90	347	12.7	75.0	12.7	35.0	13.7	66.9	49.1	1.36
I - 2.9 t - 1 S - 1	2.90	347	12.7	75.0	25.5	35.0	13.7	53.3	52.6	1.01
I - 2.9 t - 1 S - 2	2.90	347	12.7	75.0	25.5	35.0	13.7	57.5	52.6	1.09
I - 2.9 t - 1 S - 3	2.90	347	12.7	75.0	25.5	35.0	13.7	70.5	52.6	1.34
I-2.9t-0.5S-1	2.90	347	12.7	75.0	12.7	35.0	13.7	53.3	49.1	1.09
I-2.9t-0.5S-2	2.90	347	12.7	75.0	12.7	35.0	13.7	54.2	49.1	1.10
I-4t-0.5S-1	4.09	555	12.7	75.0	12.7	35.0	13.7	117	110.7	1.06
I-4t-0.5S-2	4.09	555	12.7	75.0	12.7	35.0	13.7	119	110.7	1.08
I-4t-0.5S-3	4.09	555	12.7	75.0	12.7	35.0	13.7	120	110.7	1.08
I-4t-1.0S-1	4.09	555	12.7	75.0	25.4	35.0	13.7	128	118.5	1.08
I-4t-1.0S-2	4.09	555	12.7	75.0	25.4	35.0	13.7	122	118.5	1.03
I-4t-1.0S-3	4.09	555	12.7	75.0	25.4	35.0	13.7	127	118.5	1.07
									Average	1.10
									Standard Deviation	0.10

Table 6 Summary of Test Results, 3 Bolt Tests, Single Shear Connections

Specimen ID	t (mm)	F_u (MPa)	d (mm)	w (mm)	s (mm)	g (mm)	h (mm)	P_{tested} (kN)	$T_{n,\ NR}$ (kN)	P_{tested} ---------- $T_{n,\ NR}$
O-1.6t-0.5S-1	1.59	422	12.7	110	12.7	35.0	13.7	54.7	47.8	1.14
O-1.6t-1.0S-1	1.59	422	12.7	110	25.4	35.0	13.7	60.5	52	1.15
O-1.6t-1.0S-2	1.59	422	12.7	110	25.4	35.0	13.7	60.5	52	1.15
O-2.1t-0.5S-1	2.10	447	12.7	110	12.7	35.0	13.7	74.7	67	1.12
O-2.1t-0.5S-2	2.10	447	12.7	110	12.7	35.0	13.7	73.7	67	1.10
O-2.1t-1.0S-1	2.10	447	12.7	110	25.4	35.0	13.7	81.9	73	1.12
O-2.1t-1.0S-1	2.10	447	12.7	110	25.4	35.0	13.7	80.6	73	1.10
O-4t-0.5S-1	4.07	675	12.7	110	12.7	35.0	13.7	212	196	1.08
O-4t-0.5S-2	4.07	675	12.7	110	12.7	35.0	13.7	215	196	1.10
O-4t-1.0S-1	4.07	675	12.7	110	25.4	35.0	13.7	226	215	1.05
O-4t-1.0S-2	4.07	675	12.7	110	25.4	35.0	13.7	228	215	1.06
O-5t-0.5S-1	4.93	609	12.7	110	12.7	35.0	13.7	239	214	1.12
O-5t-0.5S-2	4.93	609	12.7	110	12.7	35.0	13.7	241	214	1.13
O-5t-1.0S-1	4.93	609	12.7	110	25.4	35.0	13.7	256	235	1.09
O-6t-0.5S-1	5.98	375	12.7	110	12.7	35.0	13.7	183	160	1.15
O-6t-0.5S-2	5.98	375	12.7	110	12.7	35.0	13.7	183	160	1.15
O-6t-1.0S-1	5.98	375	12.7	110	25.4	35.0	13.7	183	175	1.04
									Average	1.11
									Standard Deviation	0.04

Table 7 Summary of Test Results, 3 Bolt Tests, Double Shear Connections, Inside Sheet Controlling

Specimen ID	t (mm)	F_u (MPa)	d (mm)	w (mm)	s (mm)	g (mm)	h (mm)	P_{tested} (kN)	$T_{n,\ NR}$ (kN)	$\frac{P_{tested}}{T_{n,\ NR}}$
I-1.6t-0.5S-1	1.59	422	12.7	110	12.7	35.0	13.7	56.2	47.8	1.18
I-2.1t-0.5S-1	2.10	447	12.7	110	12.7	35.0	13.7	73.2	66.8	1.10
I-2.1t-0.5S-2	2.10	447	12.7	110	12.7	35.0	13.7	74.0	66.8	1.11
I-2.1t-0.5S-3	2.10	447	12.7	110	12.7	35.0	13.7	74.7	66.8	1.12
I-2.1t-1.0S-1	2.10	447	12.7	110	25.4	35.0	13.7	78.9	73.3	1.08
I-2.1t-1.0S-2	2.10	447	12.7	110	25.4	35.0	13.7	80.9	73.3	1.10
I-2.1t-1.0S-3	2.10	447	12.7	110	25.4	35.0	13.7	81.0	73.3	1.10
I-4t-0.5S-1	4.07	675	12.7	110	12.7	35.0	13.7	212	196	1.08
I-4t-0.5S-2	4.07	675	12.7	110	12.7	35.0	13.7	212	196	1.08
I-4t-1.0S-1	4.07	675	12.7	110	25.4	35.0	13.7	230	215	1.07
I-4t-1.0S-2	4.07	675	12.7	110	25.4	35.0	13.7	229	215	1.07
I-6t-0.5S-1	5.98	375	12.7	110	12.7	35.0	13.7	175	160	1.10
I-6t-0.5S-2	5.98	375	12.7	110	12.7	35.0	13.7	180	160	1.13
I-6t-1.0S-1	5.98	375	12.7	110	25.4	35.0	13.7	191	175	1.09
I-6t-1.0S-2	5.98	375	12.7	110	25.4	35.0	13.7	192	175	1.10
									Average	1.10
									Standard Deviation	0.03