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Single Bolted Tension Member Design – A New Approach

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Abstract

The "2001 North American Specification for the Design of Cold-Formed Steel Structural Members" (NAS) incorporates the design of bolted tension members in country specific appendices, A, B and C. Accordingly, bolted tension members are designed differently in Canada, the United States and Mexico. The main differences between the country specific appendices are the longitudinal shear predictor equations, otherwise referred to as end pull out, as well as the inclusion of the "Effective Net Section" approach in the U.S. appendix. Consequently, the objective of this paper was to examine the most suitable approach for the design of single bolted tension members and to provide an improved design approach. In conclusion, a unified design approach is suggested for possible inclusion into the main body of the NAS. A total of 299 tests were carried out at the University of Waterloo and an additional 694 data values were taken from other researchers, resulting in a total database of 993.

The range of parameters of the test specimens were: 179 MPa (26.0 ksi) < F_y < 651 MPa (94.4 ksi), 284 MPa (41.2 ksi) < F_u < 817 MPa (118 ksi), 1.64 < d/t < 34.9, 0.042 < d/w < 0.53, and 0.82 < e/d < 7.87.

Introduction

In 2001, the North American Specification for the Design of Cold-formed Steel Structural Members (herein referred to as the NAS) was published. The Specification is the result of a collaborative effort between the American Iron and Steel Institute (AISI), the Canadian Standards Associations (CSA), and

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Camara Nacional de la Industria del Hierro y del Acero (CANACERO) of Mexico. The joint committee was charged with the objective of unifying the technical design provisions relevant to cold-formed steel design within the three countries. Where the three countries could not reach consensus regarding a technical provision, the provision was placed in the respective country-specific appendices, which was the case with bolted tension members. It should be noted that Appendix C for Mexico is the same as Appendix A for the U.S.

The objective of the research summarized in this paper was to establish a common design approach for single bolted tension members for possible adoption by the NAS. The objective was accomplished by using data from various researchers, including data from a testing program conducted at the University of Waterloo.

Differences between the U.S. and Canadian Country Specific Appendices

Two main differences are included in the Canadian (CSA, 2002) and U.S. (AISI, 2002) country specific appendices with regards to single bolted tension members, these being:

1. Difference in the nominal longitudinal shear (or end pull out) capacity, P_n:

   a. Canada: $P_n = 2(e - 0.5h)t(0.6F_u)$ (1)

   b. U.S.: $P_n = 2et(0.5F_u) = teF_u$ (2)

   Where, F_u is the ultimate strength of the sheet material, and the dimensional parameters are as shown in Figure 1.

2. Inclusion of an "Effective Net Section" approach to calculate the nominal tensile capacity, P_n, which is only found in the U.S. appendix:

   a. $P_n = A_nF_t$ (3)

   Where A_n is the net area of the connected part (gross area less the cross sectional hole area), and F_t is the nominal tensile stress in the sheet and is calculated as follows:

For single bolted connections with washers under both bolt head and nut:

$$F_t = \left(0.1 + 3\, d/s\right) F_u \le F_u \qquad (4)$$

For single bolted connections without washers or with only one washer under the bolt head or the nut:

$$F_t = \left(2.5\, d/s\right) F_u \le F_u \qquad (5)$$

Where d is the nominal bolt diameter and s is the sheet width, w, divided by the number of bolts in the cross section. For single bolted connections, d/s reduces to d/w.

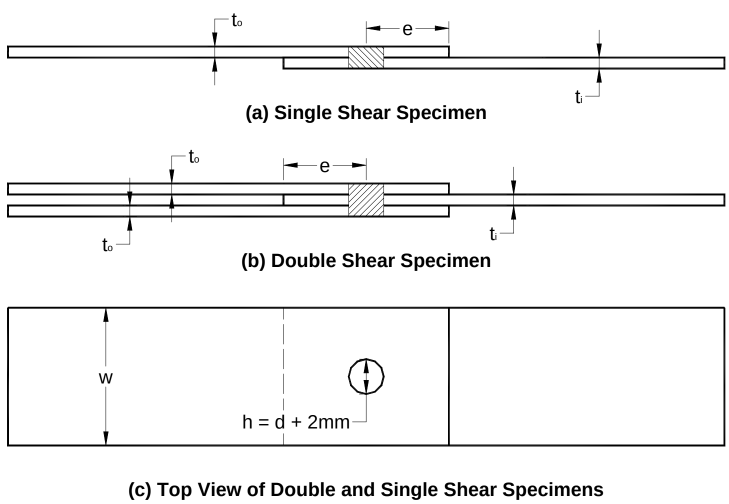


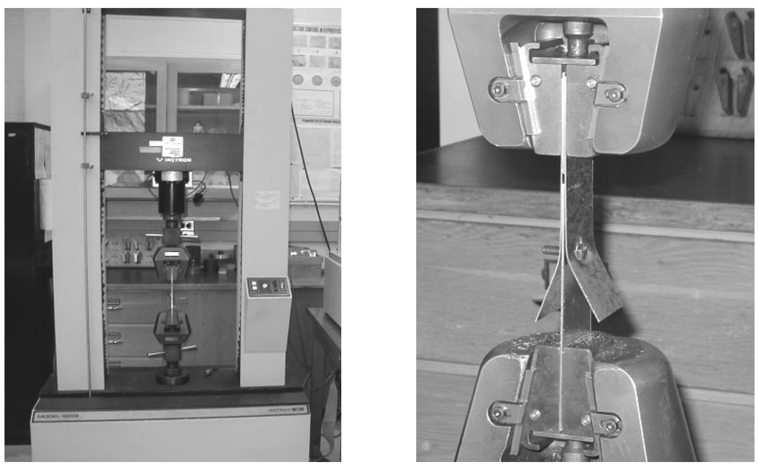
Figure 1 Dimensions of Typical Single Bolted Tension Member

Test Program

A test program was conducted at the University of Waterloo on 299 single bolted specimens. Test specimens were fabricated by manual shearing and hole punching as well as by laser cutting for improved accuracy, especially for narrow sheet widths. Various configurations were fabricated including:

- double and single shear specimens, and
- specimens without washers and with washers under both bolt head and nut.

Specimens were tested in either the Materials Laboratory of the Mechanical Engineering Department or in the Structures Laboratory at the University of Waterloo. Specimens with large sheet widths, w, or sheet thicknesses, t, were tested in an MTS 4 Column testing machine, whereas specimens of narrow sheet width or smaller sheet thickness were tested in either an MTS 810 Material Test Machine or an Instron Model 4206. Photographs of a typical test setup are shown in Figure 2.



(a) Instron Model 4206 (b) Specimen Installed in Grips

Figure 2 Photographs of a Typical Test Setup

In all cases, the specimens were loaded at a rate of between 10 and 15mm per minute. When the peak load was observed, the test was stopped and visual observations of the failure mode and any other pertinent information was recorded. Load and displacement of the actuator were recorded electronically during each test.

Three of the four failure modes observed by Winter (1956) were observed in the test program, these being:

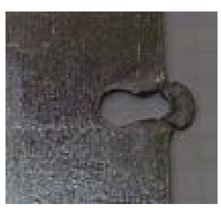
1. Longitudinal Shear Failure (Type I),

2. Bearing Failure (Type II),

3. Fracture of Net Section (Type III), and

4. Bolt Shear (not shown or discussed in this paper).

Furthermore, rotational behaviour of the plate material or excessive rotation of the bolt, which have been observed by previous researchers (Baehre & Berggren, 1971; Gilchrist & Chong, 1979; Kemp, 2001; Mosby, 1976b; Rogers & Hancock, 1997; Stark & Toma, 1978), was also observed. Shown in Figure 3 are photographs of the observed failure modes as well as of a rotational failure mode (V).



(a) Type I Failure (Shear)

(b) Type II Failure (Bearing)

(c) Type III Failure (Net Section)

(d) Type V Failure (Rotation)

Figure 3 Photographs of Observed Failure Modes

Accuracy of Current NAS Provisions

To analyse the accuracy of the current NAS provisions, a dataset was compiled consisting of 299 test specimens conducted as part of this research program, along with 694 tests found in the literature (Carril et al, 1994; Chong & Matlock, 1975; Dhalla et al, 1971; Kemp, 2001; McKinney, 1975; Mosby & Yu, 1976a; Mosby & Yu, 1976b; Mosby & Yu, 1978; Rogers & Hancock, 1997; Rogers & Hancock, 1998; Wallace et al, 2001; Winter, 1956; Yu & Mosby, 1981). The complete dataset of 993 test specimens can be broken down into the following categories:

1. 316 single shear specimens without washers (SS),
2. 310 single shear specimens with washers under both bolt head and nut (SSW),
3. 307 double shear specimens where the inside sheet thickness was less than the combined thickness of the outer sheets (DSI),
4. 30 double shear specimens where the combined thickness of the outside sheets was less than the thickness of the inside sheet and washers were not provided (DSO), and
5. 30 double shear specimens where the combined thickness of the outside sheets was less than the thickness of the inside sheet and washers were provided under both bolt head and nut (DSOW).

The range of parameters of the test specimens were: 179 MPa (26.0 ksi) < F_y < 651 MPa (94.4 ksi), 284 MPa (41.2 ksi) < F_u < 817 MPa (118 ksi), 1.64 < d/t < 34.9, 0.042 < d/w < 0.53, and 0.82 < e/d < 7.87.

Using the dataset, the accuracy of the current NAS provisions was analysed by calculating the nominal capacity of each test specimen, and computing the ratio of tested capacity to calculated capacity, $P_{test}/P_{calculated}$. A statistical analysis of $P_{test}/P_{calculated}$ for the entire dataset was performed and is summarized in Table 1, which is broken down by category type. $P_{calculated}$ is computed on the basis of the general provisions relevant to single bolted tension members combined with the country-specific provisions. $P_{calculated}$ based on the Canadian provisions is referred to as CSA, while $P_{calculated}$ based on the U.S. provisions is referred to as AISI.

Table 1 Summary of $P_{test}/P_{calculated}$ for Canadian and U.S. Provisions

Specimen Type	Average		Coefficient of Variation	
	CSA	**AISI**	**CSA**	**AISI**
SS	1.12	1.10	0.30	0.18
SSW	1.14	1.06	0.29	0.20
DSI	1.10	1.37	0.21	0.26
DSO	0.85	0.95	0.15	0.11
DSOW	0.90	0.92	0.12	0.10

It can be observed from Table 1 that AISI is more accurate and has less variability in predicting the capacity of SS and SSW specimens. For DSI specimens, CSA shows a significant improvement in the accuracy and prediction of the capacity with respect to AISI. Both CSA and AISI prove to be unconservative in predicting the capacity of DSO and DSOW specimens.

To further aid in determining which country-specific provisions provide the most accuracy in predicting the bolted tension member capacity, each specimen type was further broken down by observed failure mode. The results of this statistical analysis are provided in Table 2 through Table 6.

Table 2 $P_{test}/P_{calculated}$ for SS Specimens

Observed Failure Mode	Average		Coefficient of Variation	
	CSA	**AISI**	**CSA**	**AISI**
Bearing	0.97	1.05	0.21	0.15
Tearing	1.07	1.15	0.05	0.11
Shear	1.77	1.21	0.28	0.14
Rotational	1.13	1.12	0.22	0.21
Combination	1.11	1.07	0.33	0.15

Table 3 $P_{test}/P_{calculated}$ for SSW Specimens

Observed Failure Mode	Average		Coefficient of Variation	
	CSA	AISI	CSA	AISI
Bearing	1.03	1.04	0.17	0.17
Tearing	1.16	1.13	0.28	0.21
Shear	1.78	1.06	0.22	0.19
Rotational	1.06	1.06	0.31	0.31
Combination	1.07	1.06	0.21	0.21

Table 4 $P_{test}/P_{calculated}$ for DSI Specimens

Observed Failure Mode	Average		Coefficient of Variation	
	CSA	AISI	CSA	AISI
Bearing	0.98	1.51	0.26	0.34
Tearing	1.14	1.36	0.11	0.22
Shear	1.63	1.20	0.15	0.09
Combination	1.10	1.34	0.19	0.24

Table 5 $P_{test}/P_{calculated}$ for DSO Specimens

Observed Failure Mode	Average		Coefficient of Variation	
	CSA	AISI	CSA	AISI
Bearing	0.85	0.95	0.15	0.11
Tearing	-	-	-	-
Shear	-	-	-	-
Combination	-	-	-	-

Table 6 $P_{test}/P_{calculated}$ for DSOW Specimens

Observed Failure Mode	Average		Coefficient of Variation	
	CSA	AISI	CSA	AISI
Bearing	0.90	0.92	0.12	0.10
Tearing	-	-	-	-
Shear	-	-	-	-
Combination	-	-	-	-

From the preceding tables and the provisions used to calculate the predicted capacities, some general conclusions can be made:

1. Both CSA and AISI are conservative in the prediction of shear capacity. In particular, CSA is significantly more conservative with respect to AISI. It is possible that the subtraction of one half of the hole diameter from the shear path (i.e. the net shear path) is the reason for the consistently conservative shear capacity prediction in CSA, whereas the shear coefficient of 0.5 (i.e. $0.5F_u$) is the reason for the conservative predictions of AISI.

2. Based on Table 1, CSA is more accurate and has less variability in predicting the capacity of DSI specimens, whereas AISI is more accurate and exhibits less variability for SS, SSW, DSO, and DSOW specimens. Since CSA does not include the "Effective Net Section" expression, which is based on a calibration including multiple failure modes, the provision contained in CSA are for only individual failure modes, or failure modes that are predominantly one of the main modes of failure. It would follow then that, since DSI specimens exhibit no out of plane movement such as significant piling of material around the bolt or rotation of the bolt or plate material, the failure modes experienced in DSI specimens are mainly pure failure modes. On the other hand, SS, SSW, DSO and DSOW specimens tend to exhibit various out of plane behaviours such as bolt rotation, piling up of sheet material around the bolt head, and rotation of the sheet material. As such, it would follow that these types of specimens would benefit from an empirically derived expression, such as the "Effective Net Section" expression, that is based on multiple failure modes occurring simultaneously.

New Predictor Model

A new predictor model was developed based on the following objectives:

1. to increase accuracy of capacity prediction while reducing variability,

2. to reflect the conclusions found in the preceding section, and

3. to maintain a simple design approach that would be acceptable to the practitioner.

New Shear and Bearing Predictor Equations

The new shear predictor equation was developed by generating plots of the bearing coefficient, $C = F_b/F_u$, versus the e/d ratio. It is found that the empirically derived shear equation agrees with the shear equation if derived on the basis of Von Mises yield criteria. Plots were generated for SS, SSW, and DSI specimens and are presented in Figure 4 to Figure 6. For each plot, only specimens whose d/t ratio was less than 10 and whose d/w ratio was less than 0.1 were used. By imposing these limitations, better assurance can be provided that the specimens failed in pure shear. No data was available for DSO and DSOW specimens within the said parametric ratio limitations.

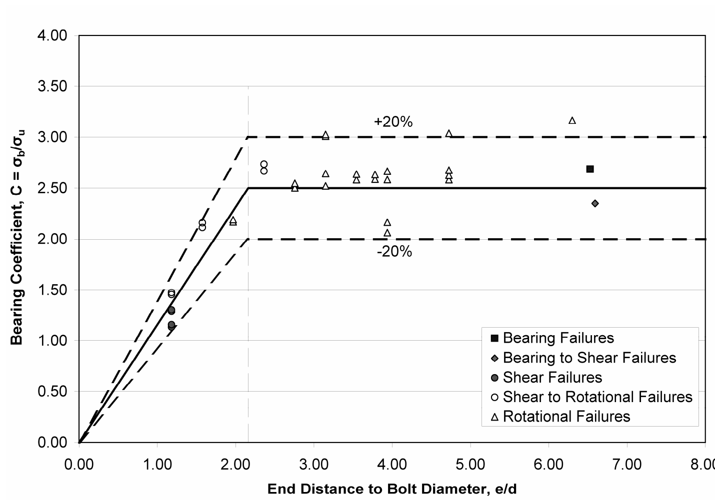


Figure 4 Coefficient C versus e/d for SS specimens

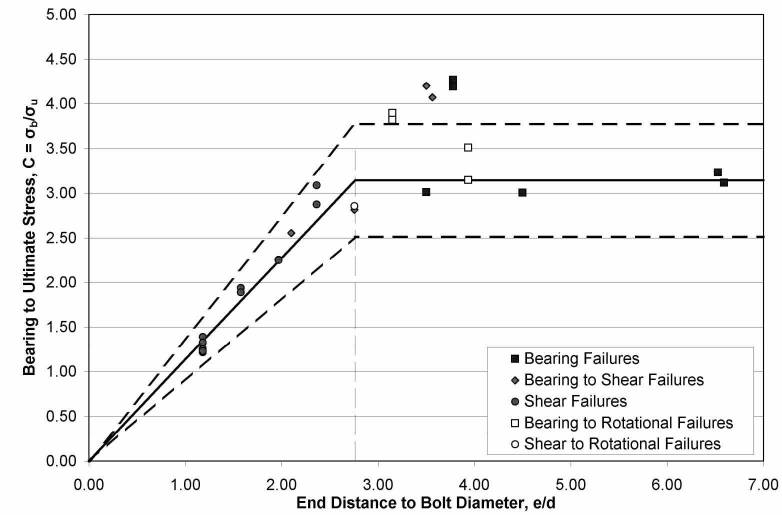


Figure 5 Coefficient C versus e/d for SSW specimens

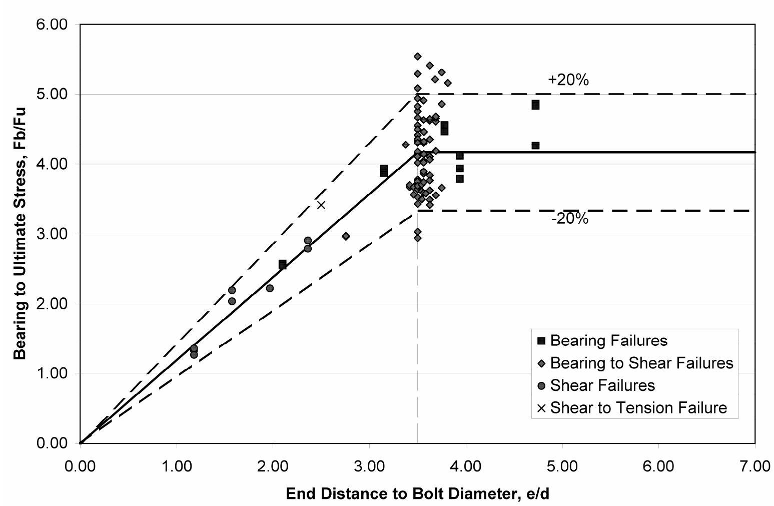


Figure 6 Coefficient C versus e/d for DSI specimens

From the preceding plots, a shear equation can be derived. The following is an example of such a derivation for SS specimens:

From Figure 4, For *e/d* $\leq$ 2.16, $F_b/F_u = 1.16\,e/d$ (6)

Using equation (6) and assuming that the shear failure is along two paths, one on either side of the bolt, the shear coefficient can be calculated as follows:

$$F_b = P/dt, \text{but } F_b = (1.16\,e/d)F_u$$

$$\therefore P = 1.16etF_u = 2et \cdot (0.58F_u) \quad (7)$$

Based on the preceding, the shear coefficient is 0.58. Using a similar approach, shear coefficients for SSW and DSI specimens can be derived and are found to be 0.57 and 0.60, respectively. All three coefficients closely match that as derived by using Von Mises yield criteria, that is $1/\sqrt{3} = 0.577$. All three derived coefficients are close to the value of 0.60, which is the common shear coefficient found in the NAS, and as such the proposed equation for the nominal shear capacity is as follows:

$$P_n = 2et \cdot (0.60F_u) \quad (8)$$

The bearing coefficients can also be derived from the same plots. As can be observed in Figure 4, the data reaches an upper limit of C = 2.50 after an e/d of 2.16, in other words:

$$F_b/F_u = 2.50 \text{ and } F_b = P/dt$$

$$\therefore P = dt(2.50F_u) \quad (9)$$

Therefore the bearing coefficient for SS specimens is 2.50. A similar process was performed for SSW and SW specimens, and the resulting bearing coefficients are summarized in Table 7. Since no data was available for DSO and DSOW specimens, the general assumption that they can be grouped with the appropriate single shear type specimens is made (i.e. SS and SSW). The proposed expression for calculating the nominal bearing capacity is as follows:

$$P_n = dt(CF_u) \quad (10)$$

Where C is the bearing coefficient based on the specimen type as found in Table 7.

Table 7 Proposed Bearing Coefficients

Specimen Type	Bearing Coefficient, C
SS and DSO Specimens	**2.50**
SSW and DSOW Specimens	**3.15**
DSI	**4.15**

Modified Effective Net Section Approach

In the accuracy analysis of the NAS, it was found that the inclusion of the "Effective Net Section" expression was beneficial for SS, SSW, DSO, and DSOW type specimens. However, the inclusion of the expression resulted in overly conservative predictions of the capacity of DSI type specimens. Therefore, a modified effective net section approach is required to better reflect the differences in the various specimen types. The approach included in the US Appendix of the NAS, referred to as the "Effective Net Section" approach, has categories for specimens with washers and specimens without washers but does not have categories based on the specimen type.

The current effective net section approach was derived on the basis of a linear regression analysis of the net section stress, $F_n = P_{net}/A_n$, divided by the ultimate stress (F_n/F_u) versus the d/w ratio. The resulting expression is:

$$F_n/F_u = m\, d/w + b \tag{11}$$

Where m is the slope of the best-fit line between the two parameters, as shown in Figure 7. The coefficients for the "Effective Net Section" approach used in the US appendix, m and b, are:

For specimens with washers

$$m = 3 \text{ and } b = 0.1 \tag{12}$$

For specimens without washers

$$m = 2.5 \text{ and } b = 0 \tag{13}$$

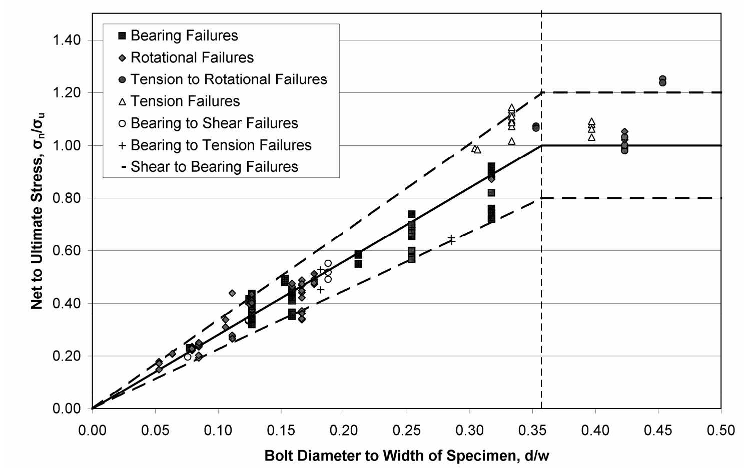


Figure 7 F_n/F_u versus d/w

A suitable modification to reflect the difference of specimen type within the effective net section approach is:

$$F_n/F_u = C_{net}\, d/w \quad (14)$$

Where C_{net} is the net section coefficient and varies based on the specimen type. Furthermore, the slenderness of the connection, d/t, was also found to have a significant effect on the net section coefficient, as shown in Figure 8, such that:

$$C_{net} = a + b\frac{d}{t} \quad (15)$$

Substituting $F_n = P_n/A_n$ into Eq. (14) and solving for P_n, the proposed modified effective net section expression is as follows:

$$P_n = C_{net}\frac{d}{w}A_nF_u \quad (16)$$

where C_{net} is defined by Eq. (15).

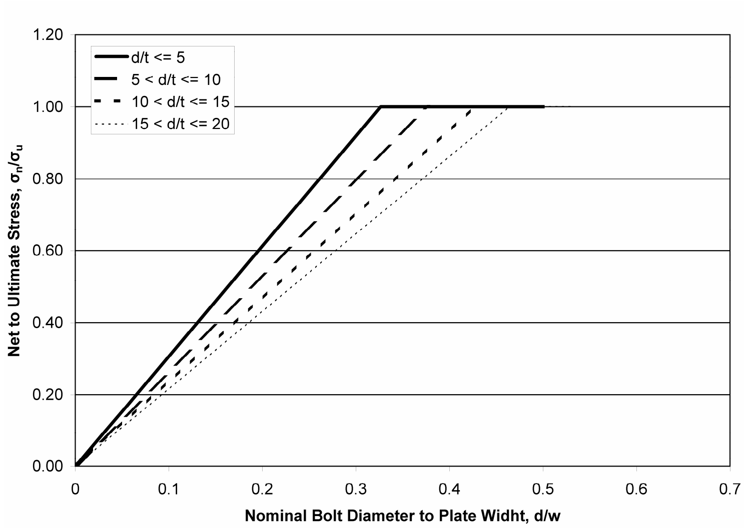


Figure 8 Variation of C_{net} with d/t ratio

To determine the regression coefficients 'a' and 'b', a multiple linear regression analysis was performed for each specimen type. Following the regression analysis, the optimization tool "Solver" in Microsoft Excel was used to optimize the regression coefficients, minimizing the standard deviation of $P_{test}/P_{calculated}$ while maintaining an average $P_{test}/P_{calculated}$ ratio of 1.0. Listed in Table 8 are the resulting coefficients for the proposed modified effective net section approach.

Table 8 Proposed Modified Effective Net Section Coefficients

Specimen Type	*a*	*b*
SS	3.25	-0.060
SSW	4.15	-0.060
DSI	4.15	0.000
DSO	2.75	-0.060
DSOW	3.60	-0.060

It should be noted that the coefficients for DSO and DSOW specimens listed in Table 8 are only based on 18 data points with a narrow range of d/t. Additional data is required to fully substantiate the ‘a’ and ‘b’ coefficients proposed for these specimen types.

It should also be noted that the coefficient ‘b’ is equal to -0.06 for each specimen type except the DSI specimens. This is perhaps a reflection that out of plane effects, such as pilling of sheet material around the bolt and bolt rotation, is significantly reduced or eliminated in DSI type specimens.

Accuracy of Proposed Prediction Equations

Using the proposed shear Eq. (8), bearing Eq. (10), and modified effective net stress Eq. (16) along with the standard tensile failure (fracture of the net section) equation, an analysis was performed to determine the accuracy of the new prediction equations. The results of the statistical analysis are provided in Table 9.

Table 9 Summary of $P_{test}/P_{calculated}$ for Proposed Prediction Equations

Specimen Type	Average	Coefficient of Variation
SS	1.00	0.18
SSW	0.98	0.20
DSI	1.00	0.22
DSO	1.00	0.07
DSOW	1.00	0.10

Comparing this with the results from the CSA and AISI analysis found in Table 1, a significant improvement in both accuracy as well as variability of capacity prediction can be observed.

Conclusions and Recommendations

Contained in this document is a summary of the research conducted at the University of Waterloo for single bolted tension members. A test program was conducted on 299 test specimens and compiled in a dataset comprised of 993 total test specimens.

An analysis of the accuracy of the provisions included in the 2001 NAS was conducted, resulting in the following observations:

1. Both CSA and AISI are conservative in the prediction of shear capacity. In particular, CSA is significantly more conservative with respect to AISI.

2. CSA is more accurate and has less variability in predicting the capacity of double shear specimens where the inside sheet controls the strength of the member, whereas AISI is more accurate and exhibits less variability for single shear specimens (with and without washers) and double shear specimens (with and without washers) where the outside sheets control the strength of the member.

A proposed design procedure was developed, which includes new shear and bearing equations, as well as a modified effective net section equation. The new design procedure results in a significant improvement in both the accuracy and variability of predicting the capacity of single bolted tension members.

Further work is required to extend the new design procedure to both multiple bolt tension members and to tension members made up of non-flat elements such as angles and channel sections.

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Appendix II – Notation

a, b	Modified "Effective Net Section" coefficients
A_n	Net cross-sectional area at location of bolt hole = Gross cross-section area less (h x t)
C	Bearing coefficient = F_b/F_u
C_{net}	Net section coefficient
d	Nominal bolt diameter
e	Distance from center of bolt to end of plate
h	Bolt hole diameter
F_b	Bearing stress at the location of the bolt
F_u	Ultimate strength
F_t, F_n	Tensile stress in the sheet
F_y	Yield strength
$P_{calculated}$, P_c, P_n	Calculated nominal strength
P_{test}, P_t	Ultimate load of test specimen
s	Sheet width divided buy the number of bolts in the cross section
t	Plate/sheet thickness
t_i	Plate/sheet thickness of inside sheet
t_o	Plate/sheet thickness of outside sheets
w	Width of plate