Net Section Tension Capacity of Bolted Connections in Cold-Reduced Steel Sheets

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Abstract:

This paper examines the accuracy of design equations specified in the North American, European and Australasian codes for cold-formed steel structures in determining the net section tension capacity of bolted connections in flat steel sheets. It points out that the shear lag factors embedded in the code equations either yield “anomalous” results or become irrelevant when they exceed unity. The “anomaly” was demonstrated through laboratory tests and is explained using simple calculus. The configurations of specimens tested in the laboratory include single shear and double shear connections, with single or double bolts in a line parallel or perpendicular to the force. A proper mathematical expression for the in-plane shear lag factor, which does not suffer from the anomaly of the code equations and never implies shear lag factors greater than unity for any configuration, is presented and shown to yield improved results compared to the current specifications. The resistance factor for the proposed equation is computed with respect to the LRFD approach given in the North American specification for the design of cold-formed steel structures.

Subject headings: bolted connections, cold-formed steel, steel plates, tensile strength

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Introduction

The net section tension capacity of a bolted connection in cold-formed steel sheet is specified in Supplement No. 2 to the North American Specification for the Design of Cold-formed Steel Structural Members 2007 (AISI 2010), in the European code EN-1993-1-3:2004 (ECS 2004), and in the Australasian code AS/NZS 4600:2005 (SA/SNZ 2005). Contrary to rational expectation and the laboratory test results presented in this paper, the code equations often predict a bolted connection to have a greater net section tension capacity if the net section area is reduced.

Another aspect of the code equations is that the computed shear lag factors often exceed unity and have to be artificially ignored in the calculation of the net section tension capacity.

In the context of the inability of the earlier Australasian and North American codes (SA/SNZ 1996, AISI 1996) to predict the failure modes of bolted connections in flat steel sheets, Rogers & Hancock (2000) pointed out that the incorrect design equations, which were carried over to the succeeding codes (SA/SNZ 2005, AISI 2007), were based on inappropriate association and/or misidentification of the bearing failure mode and the net section fracture mode of bolted connection specimens tested by the early researchers (Winter 1956, Popowich 1969, Chong & Matlock 1975). This issue has also been discussed by LaBoube (1988). Proper identification of failure modes has been described by Rogers & Hancock (2000).

In the present work, laboratory tests on single bolted connections, connections with multiple bolts in a line parallel to the force, and connections with a row of bolts perpendicular to the force were conducted to verify the current code equations. All the specimens were configured such that they would not fail in end tear-out or block shear rupture. Most specimens were loaded concentrically (double shear) while others eccentrically (single shear).

Using simple calculus, this paper explains why the shear lag factors embedded in the code equations lead to “anomalous” results as demonstrated by the laboratory tests. A mathematical form for the shear lag factor that correctly results in a reduced net section tension capacity for a reduced net section area, and that never yields values greater than unity for any connection configuration, is presented. It is shown that the new equation, which makes use of the same parameters as the code equations, is more consistent and more accurate than those specified by the design codes in determining the net section tension capacities of the tested specimens.

Code equations for net section tension capacity

All code equations in this section are applicable to connections in flat sheet without washers. The equations are empirical in nature and were derived by curve-fitting the laboratory test results obtained by various researchers in North America (Winter 1956, Popowich 1969, Chong & Matlock 1975, Yu & Mosby 1981, Fox & Schuster 2006). Some variables in the equations have been rewritten for the sake of consistency across the different codes. Resistance factors are not included in the equations.

The North American and Australasian provisions

Clause 5.3.3(b) of AS/NZS 4600:2005 (SA/SNZ 2005) and Section E3.2 in Appendix A of the 2007 North American specification (AISI 2007) specify the net section tension capacity of a connection with a single bolt or a single row of bolts perpendicular to the force to be

$$P_p = A_n F_u \left(2.5 \frac{d}{s} \right) \leq A_n F_u \quad (1)$$

in which A_n is the net area of the connected part, F_u is the material tensile strength of the connected part, d is the nominal bolt diameter, and s is the sheet width divided by the number of bolt holes in the cross-section considered. The term $2.5 d/s$ represents the shear lag factor.

According to these two codes, the equation is applicable to concentrically loaded components (double shear connection) as well as eccentrically loaded components (single shear connection). In Figure 1, which depicts the test arrangements of the present specimens, only the inner sheet of the double shear specimen is subjected to concentric loading.

In Supplement No. 2 to the North American specification (AISI 2010), Equation (1) is restricted to eccentrically loaded components. For a concentrically loaded component, the net section tension capacity is amended in Table E5.2-1 of the supplement to

$$P_p = A_n F_u \left(4.15 \frac{d}{s} \right) \leq A_n F_u \quad (2)$$

Clause 5.3.3(b) of AS/NZS 4600:2005 (SA/SNZ 2005) and Supplement No. 2 to the North American specification (AISI 2010) specify the net section tension capacity of a single or double shear connection with multiple bolts in a line parallel to the force to be

$$P_p = A_n F_u \quad (3)$$

The European provision

The European code for cold-formed steel members and sheeting EN-1993-1-3:2004 (ECS 2004) only provides one equation to determine the net section tension capacity of a bolted connection irrespective of the configuration

$$P_p = A_n F_u \left\{ 1 + 3r \left(\frac{d_h}{u} - 0.3 \right) \right\} \leq A_n F_u \quad (4)$$

in which r is the ratio of the number of bolts at the considered cross-section to the total number of bolts in the connection, d_h is the nominal bolt hole diameter, and u is the lesser of $2e_2$ and p_2 . The outer and inner bolt spacings e_2 and p_2 are defined in Figure 2.

Test materials

The G450 sheet steel materials used in the laboratory tests, which have a trade name GALVSPAN[®], were manufactured and supplied by Bluescope Steel Port Kembla Steelworks, Australia. Two nominal thicknesses were used in the present work, being 1.5 mm and 3.0 mm. The average base metal thicknesses t_{base} , yield stresses F_y , tensile strengths F_u and elongations at fracture over 15 mm, 25 mm and 50 mm gauge lengths ε_{15} , ε_{25} and ε_{50} , and uniform elongation outside the fracture ε_{u0} of the steel materials as obtained from six 12.5 mm wide tension coupons are shown in Table 1. Tensile loading of all coupons and bolted connection specimens is in the direction perpendicular to the rolling direction of the G450 sheet steel. The tension coupon tests were conducted at a constant stroke rate of 1 mm/minute resulting in a strain rate of about 2×10^{-4} per second prior to necking.

The tensile strengths in the direction perpendicular to the rolling direction of 1.5 mm and 3.0 mm G450 sheet steels obtained in the present work, rounded to the nearest 5 MPa, are 6% and 10% higher than those obtained by Teh & Hancock (2005) in the rolling direction. While Teh & Hancock (2005) did not provide the elongations at fracture, it is believed that the rolling direction is associated with higher ductility. In any case, the G450 sheet steels used in the present work represent the grades of steel covered by AS/NZS 4600 (SA/SNZ 2005) which are among those having the lowest ductility without having their nominal yield stress and nominal tensile strength artificially reduced for structural design calculations (Hancock 2007).

Specimen configurations and test arrangements

In all specimens, the edge distance e_1 defined in Figure 2 is at least 50 mm to prevent end tear-out or block shear rupture. For the serially connected specimens, the bolt spacing p_1 defined in Figure 2 is invariably 30 mm. Other dimensions are given in the next section.

Four connection types were tested, being:

- I. Concentric Single (CS) bolted connection – double shear (Figure 3a);
- II. Concentric Parallel Double (CPD) bolted connection – double shear (Figure 3b);
- III. Concentric Serial Double (CSD) bolted connection – double shear (Figure 3c); and
- IV. Eccentric Serial Double (ESD) bolted connection – single shear (Figure 3d).

The critical components of connection types I through III (CS, CPD, CSD), being the inner sheets of double shear connections, were loaded concentrically and were therefore not subject to out-of-plane failure modes.

This paper does not include the test results of Eccentric Single and Eccentric Parallel Double bolted connections in flat sheet, since such single shear specimens which are without washers will invariably fail in the tilt bearing mode for the whole range of practical ratios of bolt diameter to bolt spacing.

Connection type IV (ESD) is a single shear connection, but the 3.0 mm specimens tested in the present work mostly failed in net section fracture as the critical section was protected from out-of-plane bearing failure. The critical section corresponds to the last (second) bolt from the free end, as evident in Figure 4.

For each connection type of a given sheet thickness, 12 mm and 16 mm high strength bolts were used. The bolt holes were 1 mm larger than the corresponding nominal bolt diameters. It may be noted that the maximum diameter of a bolt hole for a 12 mm or larger bolt is restricted to the bolt diameter plus 2 mm (SA/SNZ 2005) or 1.6 mm (AISI 2007).

The bolts were only tightened by hand (no wrench was used), and no washers were used in all the tests. For the inner sheets of double shear specimens (CS, CPD, CSD), washers did not affect their net section tension capacity. The use of washers would not have improved the net

section tension capacity of a single shear specimen either, as discussed in the “Eccentric Serial Double (ESD) bolted connections – single shear” subsection.

In order to ensure the connected sheets remain vertical throughout the tensile test, a shim plate of the same thickness as the sheet was welded to one of the outer sheets of a double shear specimen at the grip end, as depicted in Figure 1(a). Shim plates were also welded to both sheets of a single shear specimen, as depicted in Figure 1(b).

The bolted sheets were gripped in such a way that prevented them from rotating in-plane, as shown in Figure 5. There was therefore no in-plane eccentricity of the tension load. In any case, Rogers & Hancock (1998), who used pin loading, found that there were no distinct change in failure modes or load capacities due to in-plane eccentricities.

The bolted connection specimens were tested to failure using an Instron 8033 universal testing machine at a stroke rate of 1 mm/minute, which coincides with that used for the tension coupon tests.

Experimental test results and discussions

In calculating the net section tension capacity P_p of a specimen predicted by design equations, the measured values of the geometric dimensions such as the base metal thickness, the overall sheet width, the bolt hole diameter and the bolt spacing, are used. However, for ease of comparisons, only the nominal values are shown in the tables following.

In computing the shear lag factors of the tested specimens, the present work adopted the approach of Eurocode 3 (ECS 2004) of using the (actual) bolt hole diameter rather than the bolt diameter, irrespective of the specifications.

Concentric Single (CS) bolted connections – double shear

Table 2 lists the relevant geometric dimensions and the test results of CS specimens (see Figure 3a for an example). The variable W denotes the sheet width, which in this case coincides with the variable s in Equations (1) and (2), and with the variable u in Equation (4). The variable t denotes the nominal thickness of the sheet.

Table 2 shows the ratios of the ultimate test load P_t to the net section tension capacity P_p predicted by Equations (1), (2) and (4), which are specified in the current Australasian, North American and European codes for such connections, respectively. It also includes the ratios obtained using Equation (3), which assumes a shear lag factor of unity.

Table 2 includes the results for CS specimens that failed in bearing. For such specimens, the actual P_t/P_p ratios with respect to net section fracture are higher than those reported in the table, as the specimens failed in bearing before reaching their net section tension capacities.

Table 2 reveals the following:

- Equation (1), which is specified in the Australasian code (SA/SNZ 2005), consistently and significantly underestimates the net section tension capacities of CS specimens, whether the specimen failed in net section fracture as shown in Figure 6(a) or in bearing as shown in Figure 6(b). The exceptions are specimens CS2a through CS2c.
- For the CS specimens, the conservatism of Equation (1) is the most extreme when the nominal d/s ratio is 13/60, as evident from the results of specimens CS7a and CS7b. If specimen CS7b had been able to reach its net section capacity rather than failing in bearing, then the resulting P_t/P_p ratio would have been even higher than 1.58.
- Equation (2), which is specified in Supplement No. 2 to the North American specification (AISI 2010), consistently overestimates the net section tension capacities of CS specimens. The overestimations were approximately 10% for some specimens.

In fact, the shear lag factor (4.15 d/s) never came into effect for all the specimens which failed in net section fracture as it was invariably greater than unity and thus ignored. All the specimens for which it came into effect failed in bearing.

- Equation (3), which assumes a shear lag factor of unity, has the same results as Equation (2) for the CS specimens which failed in net section fracture.
- Equation (4), which is specified in the European code (ECS 2004), overestimates the net section tension capacities of specimens CS2a through CS2c by some ten percent. However, for all the other CS specimens which failed in net section fracture, it is the most accurate among the four existing equations.

The following conclusions can be made from the test results of CS specimens:

- Comparisons between the results of Equation (3), which assumes a shear lag factor of unity, and those of Equation (4), which resulted in more accurate predictions for the present CS specimens, indicate that the in-plane shear lag factor of a bolted connection in flat sheet should not ideally be assumed to be unity.
- The shear lag factor embedded in Equation (1) is overly conservative.
- The shear lag factors computed from Equation (2) are irrelevant to the specimens which failed in net section fracture as they exceed unity for such specimens.

An “anomaly” of Equation (1) can be seen from the test results of the 50 mm wide specimens CS1a through CS4d, averaged and summarised in Table 3. The equation wrongly predicts the specimens with the larger hole for 16 mm bolt (CS2, CS4) to have higher net section tension capacities than those with the smaller hole for 12 mm bolt (CS1, CS3). Test results (P_t) demonstrated the opposite is true as logically expected.

Concentric Parallel Double (CPD) bolted connections – double shear

Table 4 lists the relevant geometric dimensions and the test results of CPD specimens (see Figure 3b for an example) which failed in pure net section fracture only, as illustrated in Figure 7(a). It does not include specimens that failed in block shear rupture, shown in Figure 7(b). Block shear ruptures are discussed in the companion paper (Teh & Clements 2011).

Table 4 reveals the following:

- In line with the preceding outcome for CS specimens, Equation (1) significantly underestimates the net section tension capacities of many specimens. In each of the few cases where it overestimates the capacity, the computed shear lag factor exceeded unity and was not used in the calculation of the predicted net section capacity P_p .
- Consistent with the preceding outcome for CS specimens, the in-plane shear lag factor of $4.15 d/s$ in Equation (2) never came into effect for all specimens listed in the table. Equation (2) tends to overestimate the net section tension capacities.
- Equation (3), which assumes a shear lag factor of unity, has the same results as Equation (2) discussed in the preceding point.
- Unlike the outcome for CS specimens, the shear lag factor of Equation (4) did not come into effect for all CPD specimens in the table except for CPD11. The results are therefore similar to those of Equations (2) and (3).

Concentric Serial Double (CSD) bolted connections – double shear

Table 5 lists the relevant geometric dimensions and the test results of CSD specimens (see Figure 3c for an example). It also shows the ratios of the ultimate test load P_t to the net section tension capacity P_p predicted by Equation (3), specified in the current Australasian and North American codes for such connections, and Equation (4), specified in the European code. For CSD specimens, the value of r in Equation (4) is 0.5.

Table 5 reveals the following:

- In line with the results for the CS specimens discussed in the preceding subsection, Equation (3), which assumes a shear lag factor of unity, consistently overestimates the net section tension capacities of the present CSD specimens.
- Equation (4) tends to underestimate the net section tension capacities of the CSD specimens. The underestimations for specimens CSD11a and CSD11b are about 15%.
- Specimens CSD5 through CSD7b, which had the same corresponding sheet widths and bolt diameters as specimens CS5a through CS7b discussed in the preceding subsection, were able to reach their net section tension capacities rather than failing in bearing like the single bolted specimens. This result was expected as a CSD specimen tends to double the bearing capacity of a CS specimen having the same geometric dimensions. The net section fracture of specimen CSD5 is shown in Figure 8.
- Specimens CSD9a and CSD9b failed in bearing while CSD11a and CSD11b failed in net section fracture. The only geometric difference between them is in the (nominal) sheet thickness as given in Table 5. The thinner specimens were more prone to bearing failure before their net section tension capacities were reached in the tests.
- For the 1.5 mm CSD specimens, the upper bound nominal d/s ratio below which the connection will fail in bearing prior to reaching its net section tension capacity is 0.17.

Despite the different in-plane shear lag factors specified by the design codes (AISI 2010, SA/SNZ 2005) for CSD connections and for CS connections, comparisons of the test results of the present CSD specimens and the CS specimens discussed in the “Concentric Single (CS) bolted connections – double shear” subsection suggest that a common equation can be used to predict their net section tension capacities.

An anomaly of Equation (4) similar to that of Equation (1) discussed in the “Concentric Single (CS) bolted connections – double shear” subsection can be seen from the test results of the 3.0 mm specimens CS11a through CS12b, averaged and summarised in Table 6. The equation wrongly predicts the specimens with the larger hole for 16 mm bolt (CS12a and CS12b) to have higher net section tension capacities than those with the smaller hole for 12 mm bolt (CS11a, CS11b). Test results (P_t) demonstrated the opposite is true as logically expected.

The inherent “anomaly” of Equations (1), (2) and (4) is explained using simple calculus in the next section.

Eccentric Serial Double (ESD) bolted connections – single shear

Table 7 lists the relevant geometric dimensions and the test results of ESD specimens (see Figure 3d for an example). It also shows the ratios of the ultimate test load P_t to the net section tension capacity P_p predicted by Equation (3) used in the current Australasian and North American codes for such connections, and Equation (4) used in the European code. For ESD specimens, the value of r in Equation (4) is 0.5.

Comparisons between the test results of the ESD specimens which failed in net section fracture (ESD3, ESD4, ESD8) and those of the corresponding CSD specimens (CSD3, CSD4a/b, CSD8a/b) suggest that a common equation can be used to predict the net section tension capacities of CSD and ESD bolted connections. In fact, as pointed out in the preceding subsection, the same equation can also be used for the CS bolted connections discussed in the “Concentric Single (CS) bolted connections – double shear” subsection. In the next section, only one new equation will be formulated for these three connection types.

The test results discussed in the preceding paragraph also indicate that the use of washers would not have improved the capacities of the present ESD specimens which failed in net

section fracture, which is only logical. In the case of the CSD specimens, the outer sheets had the same beneficial effects (if indeed any) on the inner sheets as washers would have.

Proposed equation

Proper expression for the shear lag factor

As highlighted in Table 3, the use of Equation (1) leads to net section tension capacities that are neither rational nor consistent with the laboratory test results. In fact, any equation of the following form

$$P_p = A_n F_u \left(k \frac{d}{s} \right) \quad (5)$$

such as Equations (1) and (2) is inherently “anomalous”. It can be shown that, for a single bolted connection where the variable s equals the sheet width W , and the net section area A_n approximates $(W - d)t$, the variation of the predicted net section tension capacity P_p with respect to the bolt diameter d is

$$\left(\frac{\partial P_p}{\partial d} \right)_{(5)} = t F_u k \left(1 - \frac{2d}{W} \right) \quad (6)$$

which means that, for a given sheet width W , the predicted net section tension capacity P_p would only decrease with increasing bolt (hole) diameter d if W is less than $2d$.

On the other hand, in practice the sheet width W is always greater than twice the bolt diameter d , so Equations (1) and (2) will either give anomalous results or reduce to Equation (3) when the computed shear lag factor is greater than unity.

The same flaw also holds for Equation (4), which results in the variation of the predicted net section strength P_p with respect to the bolt diameter d of a single bolted connection being

$$\left(\frac{\partial P_p}{\partial d}\right)_{(4)} = t F_u \left(2.9 - \frac{6d}{W}\right) \quad (7)$$

which has a very similar implication to Equation (6). The anomaly of Equation (4) has been highlighted in Table 6.

It is also shown in the preceding section that the shear lag factors embedded in Equations (1), (2) and (4) are often ignored in the net section tension capacity calculation as they become larger than unity for many configurations. Equation (2), which is specified in the current North American specification (AISI 2010), reduces to Equation (3) for all the specimens which failed in net section fracture in the present work.

Logically, a correct mathematical expression for the in-plane shear lag factor should never yield values greater than unity. It is therefore desirable that the shear lag factor is expressed as a single continuous function of the connection parameters that never implies values greater than unity. Such an expression can indeed be rationally formulated while retaining the ratio d/s or d/u used in the three cold-formed steel design codes

$$P_p = A_n F_u \left[a + b \left(\frac{d}{u} \right)^m \right]; \quad a + b = 1 \quad (8)$$

In the limit condition of a single bolted connection where the bolt diameter d approaches u (which equals the sheet width W), Equation (8) implies a shear lag factor equal to unity.

The results of Equation (3) shown in the preceding section indicate that a lower bound value of 0.9 for the shear lag factor appears to be reasonable. It is also preferable to keep the expression for the shear lag factor linear. Adopting $a = 0.9$, $b = 0.1$ and $m = 1$, Equation (8) becomes, for a connection with a single bolt or a single line of bolts parallel to the force

$$P_p = A_n F_u \left(0.9 + 0.1 \frac{d}{W} \right) \quad (9a)$$

and for a connection with a row of bolts perpendicular to the force

$$P_p = F_u \left[\sum A_{ni} \left(0.9 + 0.1 \frac{d}{p_2} \right) + \sum A_{no} \left(0.9 + 0.05 \frac{d}{e_2} \right) \right] \quad (9b)$$

in which A_{ni} refers to a net section between bolt holes, and A_{no} refers to either of the two net sections flanking the group of bolts. The variables p_2 and e_2 are defined in Figure 1.

For a single bolted connection, Equation (9) leads to

$$\left(\frac{\partial P_p}{\partial d} \right)_{(9)} = tF_u \left(-0.8 - \frac{0.2d}{W} \right) \quad (10)$$

which means that, for a given sheet width W , the predicted net section tension capacity P_p will always decrease with increasing bolt (hole) diameter d , as it should.

The shear lag factors given by Equations (1), (2), (4) and (9) over a range of d/W values for a connection with a single bolt or a single line of bolts parallel to the force are shown in Figure 9. The maximum value of d/W for a practical bolted connection imposed by the code requirement for minimum bolt spacing is 0.33.

Equation (9) yields a mean value of 1.02 for P_t/P_p of the CS, CPD, CSD, and ESD specimens which failed in net section fracture, with a standard deviation of 0.026. The individual ratios of the 51 specimens (with 32 different configurations) are shown in Figure 10.

The mean value of P_t/P_p of the same CS, CPD, CSD, and ESD specimens given by Equation (3), which assumes a shear lag factor of unity, is 0.95, with a standard deviation of 0.025. The individual ratios are shown in Figure 10. It appears that Equation (3) could be used as an alternative design equation, as suggested by Rogers & Hancock (1998), provided the correct resistance factor is applied. Within the practical range of d/u where a bolted connection fails purely by net section fracture, the shear lag factors do not vary significantly.

Figure 11 plots the P_t/P_p values given by the code equations and Equation (9). Equation (1) is specified by the Australasian code (SA/SNZ 2005) for the CS and CPD specimens only, and Equation (4) is specified by the European code (ECS 2004) for all the specimens tested in the present work. Since the in-plane shear lag factor embedded in Equation (2) never came into effect for all the specimens which failed in net section fracture and therefore the equation reduced to Equation (3), its results are not shown in Figure 11.

Resistance factor (or capacity reduction factor)

Based on the results discussed in the preceding subsection, Equation (9) is proposed to be used for determining the net section tension capacity of a bolted connection in cold-reduced steel sheet. The relative reliability of structural design rules including the design equations for connections is described in terms of a reliability index, commonly denoted β . A larger value of β indicates a greater reliability. The target reliability index β_0 for a connection is 3.5, which is recommended in Section F1.1 of the North American specification (AISI 2007) and in the commentary to Clause 1.6.2.2 of the Australasian code (SA/SNZ 1998).

Section F1.1 of the North American specification (AISI 2007) specifies that the resistance factor ϕ of a design equation is determined as follows

$$\phi = C_\phi (M_m F_m P_m) e^p \quad (11)$$

in which C_ϕ is the calibration coefficient equal to 1.52 in the case of the Load and Resistance Factor Design (LRFD), M_m is the mean value of the material factor equal to 1.187 in the present case, F_m is the mean value of the fabrication factor equal to 0.99, and P_m is the mean value of the professional factor equal to 1.02 as stated in the preceding subsection. The statistical parameters of the material and fabrication factors of the (unwelded) 1.5 mm and 3.0 mm G450 sheet steels have been previously provided by Teh & Hancock (2005).

The power p of the natural logarithmic base e in Equation (11) is

$$p = -\beta_0 \sqrt{V_M^2 + V_F^2 + C_p V_P^2 + V_Q^2} \quad (12)$$

in which V_M is the coefficient of variation of the material factor equal to 0.03 in the present case, V_F is the coefficient of variation of the fabrication factor equal to 0.02, V_P is the coefficient of variation of the professional factor equal to 0.065 being the minimum value specified in Section F1.1 of the specification, C_p is the correction factor equal to 1.06 as computed from the relevant equation given in Section F1.1, and V_Q is the coefficient of variation of load effects equal to 0.21 as specified in Section F1.1.

It was found that in order to achieve the target reliability index β_0 of 3.5 in the LRFD, Equation (11) yields a resistance factor of 0.84. A resistance factor ϕ equal to 0.80 (rounded down to the nearest 0.05) in conjunction with Equation (9) is therefore recommended. This value is higher than the current value of 0.65 specified in the cold-formed steel design codes (AISI 2007, SA/SNZ 2005), reflecting the greater reliability of the proposed Equation (9) compared to Equations (1) through (3).

Conclusions

The in-plane shear lag factors embedded in the design equations specified in the North American, European and Australasian cold-formed steel codes for determining the net section tension capacity of a bolted connection in steel sheet have been shown to yield “anomalous” results. The current shear lag factors cause the code equations to wrongly predict a bolted connection to have a greater net section tension capacity if the net section area is reduced, contrary to the rational expectation and the laboratory test results presented in this paper.

It was also found that the shear lag factors computed using the current codes often exceeded unity, and have to be ignored in the calculation of the net section tension capacity.

The “anomaly” of the shear lag factors embedded in the code equations is explained using simple calculus, and a new mathematical expression for the in-plane shear lag factor of bolted connections in cold-reduced steel sheets is proposed. The new expression, which makes use of the same parameters as the current code equations, does not suffer from the anomaly and never implies shear lag factors greater than unity for any connection configuration.

The new equation proposed in this paper has been shown to yield more consistent and more accurate results in predicting the net section tension capacities of bolted connections in cold-reduced steel sheets compared to the design equations specified in the current cold-formed steel codes.

It is proposed that a resistance factor of 0.80 be applied to the new equation in order to ensure a reliability index of not less than 3.5 in the LRFD approach of the North American specification for the design of cold-formed steel structures.

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Notation

A_n = net area of considered section

C_p = correction factor

C_ϕ = calibration coefficient

d = bolt diameter

d_h = bolt hole diameter

e_2 = outer bolt spacing

F_m = mean value of fabrication factor

F_u = tensile strength of steel material

F_y = yield stress of steel material

k = a coefficient of shear lag factor

M_m = mean value of material factor

p_2 = inner bolt spacing

P_m = mean value of professional factor

P_p = predicted failure load

s = sheet width divided by the number of bolt holes in the considered section

t = nominal sheet thickness

t_{base} = base metal thickness

u = lesser of $2e_2$ and p_2

V_F = coefficient of variation of fabrication factor

V_M = coefficient of variation of material factor

V_P = coefficient of variation of professional factor

V_Q = coefficient of variation of load effects

W = sheet width

β_0 = target reliability index

ε_{15} = elongation at fracture over a gauge length of 15 mm

ε_{25} = elongation at fracture over a gauge length of 25 mm

ε_{50} = elongation at fracture over a gauge length of 50 mm

ε_{u0} = uniform elongation outside fracture zone

ϕ = resistance factor (or capacity reduction factor)

Table 1 Average material properties

	t_{base}	F_y	F_u	F_u / F_y	ϵ_{15}	ϵ_{25}	ϵ_{50}	ϵ_{u0}
	(mm)	(MPa)	(MPa)		(%)	(%)	(%)	(%)
1.5 mm	1.48	605	630	1.04	21.3	18.0	12.0	6.8
3.0 mm	2.95	530	580	1.09	29.3	22.0	15.3	8.1

Table 2 Results of Concentric Single (CS) bolted specimens

Spec	W or s or u (mm)	t (mm)	d_h (mm)	Failure Mode	P_t/P_p			
					(1)	(2)	(3)	(4)
CS1a	50	1.5	13	Net Section	1.27	0.93*	0.93	0.95
CS1b	50	1.5	13	Net Section	1.41	0.91*	0.91	1.04
CS2a	50	1.5	17	Net Section	1.02	0.91*	0.91	0.91*
CS2b	50	1.5	17	Net Section	1.00	0.88*	0.88	0.88*
CS2c	50	1.5	17	Net Section	1.02	0.91*	0.91	0.91*
CS3a	50	3.0	13	Net Section	1.37	0.91*	0.91	1.02
CS3b	50	3.0	13	Net Section	1.40	0.94*	0.94	1.04
CS3c	50	3.0	13	Net Section	1.40	0.94*	0.94	1.02
CS4a	50	3.0	17	Net Section	1.11	0.98*	0.98	0.98*
CS4b	50	3.0	17	Net Section	1.12	0.97*	0.97	0.97*
CS4c	50	3.0	17	Net Section	1.08	0.98*	0.98	0.98*
CS4d	50	3.0	17	Net Section	1.09	0.98*	0.98	0.98*
CS5a	60	1.5	13	Bearing	1.41	0.85	0.76	1.02
CS5b	60	1.5	13	Bearing	1.31	0.79	0.69	0.94
CS6a	60	1.5	17	Net Section	1.30	0.94*	0.94	0.97
CS6b	60	1.5	17	Bearing	1.29	0.89*	0.89	0.96
CS7a	60	3.0	13	Bearing	1.53	0.92	0.90	1.12
CS7b	60	3.0	13	Bearing	1.58	0.95	0.83	1.13
CS8a	60	3.0	17	Net Section	1.36	0.98*	0.98	1.02
CS8b	60	3.0	17	Net Section	1.35	0.95*	0.95	1.01
CS8c	60	3.0	17	Net Section	1.33	0.93*	0.93	0.99
CS8d	60	3.0	17	Net Section	1.36	0.94*	0.94	1.01

*The computed shear lag factor is not used as it exceeds unity.

Table 3 Anomaly of Equation (1)

Spec	t (mm)	d_h (mm)	P_t (kN)	(1) (kN)
CS1	1.5	13	31.4	23.4
CS2	1.5	17	27.2	26.8
CS3	3.0	13	58.7	42.4
CS4	3.0	17	54.2	49.2

Table 4 Results of Concentric Parallel Double (CPD) bolted specimens

Spec	W	p_2	t	d_h	P_t/P_p			
	(mm)	(mm)	(mm)	(mm)	(1)	(2)	(3)	(4)
CPD1	75	25	1.5	13	1.04	0.93*	0.93	0.93*
CPD2	75	25	1.5	17	0.95*	0.95*	0.95	0.95*
CPD3	75	25	3.0	13	1.09	0.98*	0.98	0.98*
CPD4	75	25	3.0	17	0.95*	0.95*	0.95	0.95*
CPD5	80	30	1.5	13	1.12	0.96*	0.96	0.96*
CPD6	80	30	1.5	17	0.96*	0.96*	0.96	0.96*
CPD7B	80	30	3.0	13	1.18	0.98*	0.98	0.98*
CPD8	80	30	3.0	17	0.97*	0.97*	0.97	0.97*
CPD10	100	50	1.5	17	1.14	1.00*	1.00	1.00*
CPD11	100	50	3.0	13	1.44	0.98*	0.98	1.05
CPD12	100	50	3.0	17	1.17	1.00*	1.00	1.00*

*The computed shear lag factor is not used as it exceeds unity.

Table 5 Results of Concentric Serial Double (CSD) bolted specimens

Spec	W or u	t	d_h	Failure	P_t/P_p	
	(mm)	(mm)	(mm)	Mode	(3)	(4)
CSD1a	50	1.5	13	Net Section	0.95	1.01
CSD1b	50	1.5	13	Net Section	0.95	1.02
CSD2a	50	1.5	17	Net Section	0.96	0.96*
CSD2b	50	1.5	17	Net Section	0.97	0.97*
CSD3	50	3.0	13	Net Section	0.97	1.03
CSD4a	50	3.0	17	Net Section	0.95	0.95*
CSD4b	50	3.0	17	Net Section	0.97	0.97*
CSD5	60	1.5	13	Net Section	0.94	1.07
CSD6a	60	1.5	17	Net Section	0.92	0.96
CSD6b	60	1.5	17	Net Section	0.93	0.96
CSD7a	60	3.0	13	Net Section	0.96	1.10
CSD7b	60	3.0	13	Net Section	0.97	1.11
CSD8a	60	3.0	17	Net Section	0.97	1.00
CSD8b	60	3.0	17	Net Section	0.98	1.02
CSD9a	70	1.5	13	Bearing	0.85	1.02
CSD9b	70	1.5	13	Bearing	0.83	1.00
CSD10a	70	1.5	17	Net Section	0.92	1.01
CSD10b	70	1.5	17	Net Section	0.94	1.03
CSD11a	70	3.0	13	Net Section	0.95	1.14
CSD11b	70	3.0	13	Net Section	0.96	1.17
CSD12a	70	3.0	17	Net Section	0.95	1.05
CSD12b	70	3.0	17	Net Section	0.96	1.06

*The computed shear lag factor is not used as it exceeds unity.

Table 6 Anomaly of Equation (4)

Spec	d_h (mm)	P_t (kN)	(4) (kN)
CS11	13	94.1	81.5
CS12	17	88.0	83.6

Table 7 Results of Eccentric Serial Double (ESD) bolted specimens

Spec	W or u	t	d_h	Mode	P_t/P_p	
	(mm)	(mm)	(mm)		(3)	(4)
ESD1	50	1.5	13	Tilt Bearing	0.89	0.95
ESD2	50	1.5	17	Tilt Bearing	0.93	0.93*
ESD3	50	3.0	13	Net Section	0.96	1.04
ESD4	50	3.0	17	Net Section	0.98	0.98*
ESD5	60	1.5	13	Tilt Bearing	0.75	0.85
ESD6	60	1.5	17	Tilt Bearing	0.90	0.93
ESD7	60	3.0	13	Tilt Bearing	0.90	1.03
ESD8	60	3.0	17	Net Section	0.94	0.97

*The computed shear lag factor is not used as it exceeds unity.

Figure 1 Test arrangements of specimens

Figure 2 Definitions of geometric variables of a bolted connection

Figure 3 Four connection types tested in the present work

Figure 4

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Figure 4 Net section fracture of an Eccentric Serial Double specimen (single shear)

Figure 5 Clamped end of specimen

Figure 6 Failure modes of CS specimens

Figure 7

[Click here to download Figure: Figure 7.pdf](#)

(a) Net section fracture

(b) Block shear rupture

Figure 7 Failure modes of CPD specimens

Figure 8 Net section fracture of specimen CSD5

Figure 9
[Click here to download Figure: Figure 9.pdf](#)

Figure 9 Shear lag factors of single bolted connections as functions of d/W

Figure 10
[Click here to download Figure: Figure 10.pdf](#)

Figure 10 P_t/P_p using Equations (9) and (3)

Figure 11

[Click here to download Figure: Figure 11.pdf](#)

Figure 11 P_t/P_p using code equations and Equation (9)

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