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Lip H. Teh

Benoit P. Gilbert

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Twenty-First International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, USA, October 24 & 25, 2012

In-plane Shear Lag of Bolted Connections

Lip H. Teh[1] and Benoit P. Gilbert[2]

Abstract

This paper points out that the shear lag factors embedded in the design equations specified in the North American, European and Australasian cold-formed steel structures codes for determining the net section tension capacity of bolted connections in flat steel sheets either yield "anomalous" results or become irrelevant when they exceed unity. The anomaly is demonstrated through laboratory tests and is explained using simple calculus. 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 found to yield improved results compared to the current code equations. A resistance factor of 0.8 for the proposed equation is determined with respect to the LRFD approach given in the North American specification for the design of cold-formed steel structures.

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 Cold-formed Steel Structures (SA/SNZ 2005). Contrary to rational expectation and laboratory test results, 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

[1]Senior Lecturer, School of Civil, Mining & Environmental Engineering, University Of Wollongong, Wollongong, NSW 2500, AUSTRALIA.
[2]Lecturer, School of Engineering, Griffith University, Gold Coast, QLD 4222, AUSTRALIA.

computed shear lag factors often exceed unity and have to be artificially ignored in the calculation of the net section tension capacity.

Using simple calculus, this paper explains why the in-plane 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 specimens tested in the present work.

Code equations accounting for in-plane shear lag in bolted connections

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

$$R_n = A_n F_u \left(2.5\, {d}/{s}\right) \leq A_n F_u \tag{1}$$

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 in-plane 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

$$R_n = A_n F_u \left(4.15\, {d}/{s}\right) \leq A_n F_u \tag{2}$$

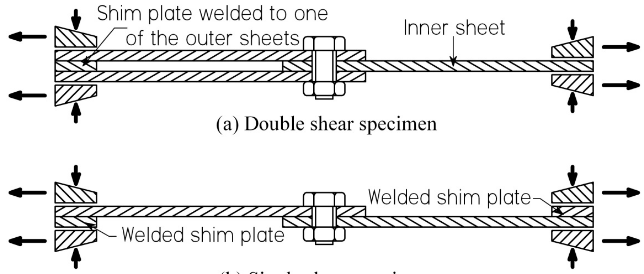

Figure 1 Test arrangements of specimens

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

$$R_n = A_n F_u \tag{3}$$

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

$$R_n = A_n F_u \left\{ 1 + 3r \left({d_h}/{u} - 0.3 \right) \right\} \le A_n F_u \tag{4}$$

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 2 e_2 and p_2, defined in Figure 2.

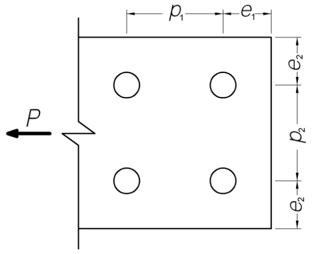

Figure 2 Definitions of geometric variables of a bolted connection

Test materials

The G450 sheet steel materials used in the laboratory tests, which have a trade name GALVASPAN®, 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 fracture ε_{uo} 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.

Table 1 Average material properties

	t_{base} (mm)	F_y (MPa)	F_u (MPa)	F_u / F_y	ε_{15} (%)	ε_{25} (%)	ε_{50} (%)	ε_{uo} (%)
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

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. It should also be noted that, with regard to the orientation of the tension coupon, Clause 2.3.2.2 of AS 1397-2011 (SA 2011) specifies that the tensile test piece "shall be cut parallel to the direction of rolling", which would result in more ductile parameters compared to the present coupons, which were cut transverse to the direction of rolling.

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 unless noted otherwise. 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).

(a) CS (b) CPD (c) CSD (d) ESD

Figure 3 Four connection types tested in the present work

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.

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. In the specifications, 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). It should be noted that the measured bolt hole diameters were used in the evaluations of the design equations, and the actual bolt hole diameter shall be used in design calculations.

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. There was therefore no in-plane eccentricity of the tension load.

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 R_n 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 legibility, only the nominal values are shown in the tables following.

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 R_n 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 of CS specimens that failed in bearing. For such specimens, the actual P_t/R_n 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 4(a) or in bearing as shown in Figure 4(b). The exceptions are specimens CS2a through CS2c.

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/R_n (1)	(2)	(3)	(4)
CS1a	50	1.5	13	NSF	1.27	0.93*	0.93	0.95
CS1b	50	1.5	13	NSF	1.41	0.91*	0.91	1.04
CS2a	50	1.5	17	NSF	1.02	0.91*	0.91	0.91*
CS2b	50	1.5	17	NSF	1.00	0.88*	0.88	0.88*
CS2c	50	1.5	17	NSF	1.02	0.91*	0.91	0.91*
CS3a	50	3.0	13	NSF	1.37	0.91*	0.91	1.02
CS3b	50	3.0	13	NSF	1.40	0.94*	0.94	1.04
CS3c	50	3.0	13	NSF	1.40	0.94*	0.94	1.02
CS4a	50	3.0	17	NSF	1.11	0.98*	0.98	0.98*
CS4b	50	3.0	17	NSF	1.12	0.97*	0.97	0.97*
CS4c	50	3.0	17	NSF	1.08	0.98*	0.98	0.98*
CS4d	50	3.0	17	NSF	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	NSF	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	NSF	1.36	0.98*	0.98	1.02
CS8b	60	3.0	17	NSF	1.35	0.95*	0.95	1.01
CS8c	60	3.0	17	NSF	1.33	0.93*	0.93	0.99
CS8d	60	3.0	17	NSF	1.36	0.94*	0.94	1.01

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

- 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/R_n 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.

(a) Net section fracture, CS8b (b) Bearing failure, CS5a

Figure 4 Failure modes of CS specimens

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 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.

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

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.

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

Spec	***W*** **(mm)**	p_2 **(mm)**	***T*** **(mm)**	d_h **(mm)**	P_t/R_n			
					(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 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 R_n.

- 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 R_n 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.

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

Spec	*W* or *u* (mm)	*t* (mm)	d_h (mm)	Failure Mode	P_t/R_n (3)	P_t/R_n (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.

- 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.

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.

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

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 R_n predicted by Equation (3) used in the current Australasian and North American codes for such connections, and Equation (4) used in the European code.

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

Spec	W or u (mm)	t (mm)	d_h (mm)	Mode	P_t/R_n	
					(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.

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. The same also applies the CS bolted connections discussed in the "Concentric Single (CS) bolted connections – double shear" subsection.

Proposed equation

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

$$R_n = A_n F_u \left(k \, {}^{d}\!/_{s}\right) \tag{5}$$

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 R_n with respect to the bolt diameter d is

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

which means that, for a given W, the predicted net section tension capacity R_n 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)

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

It is also shown in the preceding section that the in-plane shear lag factors embedded in Equations (1), (2) and (4) are often ignored in the calculation as they become larger than unity for many configurations. It is desirable that the shear lag factor is expressed as a single continuous function of the connection parameters that never implies values greater than unity, which is given by

$$R_n = A_n F_u \left(0.9 + 0.1 \, {}^{d}\!/_{W}\right) \tag{8a}$$

for a connection with a single bolt or a single line of bolts parallel to the force, and, for a connection with a row of bolts perpendicular to the force

$$R_n = F_u\left[\sum A_{ni}\left(0.9+0.1\, {d}/{p_2}\right)+\sum A_{no}\left(0.9+0.05\, {d}/{e_2}\right)\right] \tag{8b}$$

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 2.

For a single bolted connection, Equation (8) leads to

$$\left(\frac{\partial R_n}{\partial d}\right)_{(8)} = tF_u\left(-0.8-\frac{0.2d}{W}\right) \tag{9}$$

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

The shear lag factors given by Equations (1), (2), (4) and (8) 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 5.

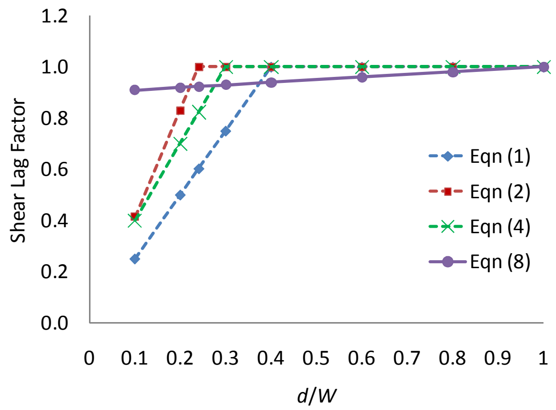

Figure 5 In-plane shear lag factors of single bolted connections

Equation (8) yields a mean professional factor of 1.02 for the CS, CPD, CSD, and ESD specimens, with a standard deviation of 0.026. It was found that in order to achieve or exceed the target reliability index β_0 of 3.5 in the LRFD, a resistance factor of 0.84 is required. This value is significantly higher than the current resistance factor of 0.65 specified in the design codes.

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 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 rational expectation and the laboratory test results. It was also found that the shear lag factors computed using the current codes often exceeded unity.

The "anomaly" of the shear lag factors embedded in the code equations has been 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 resulting equation yields more consistent and more accurate results in predicting the net section tension capacities of the tested specimens compared to the design equations specified in the current cold-formed steel structures codes.

It is proposed that a resistance factor of 0.80 (rounded down from the computed 0.84) be applied to the new equation.

References

AISI (2010) *Supplement No. 2 to the North American Specification for the Design of Cold-formed Steel Structural Members 2007 Edition*, American Iron and Steel Institute, Washington DC.

ECS (2004) *Eurocode 3: Design of steel structures, Part 1-3: General rules – Supplementary rules for cold-formed members and sheeting*, EN 1993-1-3:2004, European Committee for Standardisation, Brussels, Belgium.

Hancock, G. J. (2007) *Design of Cold-Formed Steel Structures*, 4th ed., Australian Steel Institute, Sydney.

SA (2011) Continuous hot-dip metallic coated steel sheet and strip—Coatings of zinc and zinc alloyed with aluminium and magnesium, AS 1397-2011, Standards Australia.

SA/SNZ (2005) Cold-Formed Steel Structures, AS/NZS 4600:2005, Standards Australia/Standards New Zealand.

Teh, L. H., and Hancock, G. J. (2005) "Strength of welded connections in G450 sheet steels." *J. Struct. Eng.*, 131 (10), 1561-1569.