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PROPOSED NZS 3404 BLOCK SHEAR STEEL CONNECTION DESIGN PROVISIONS

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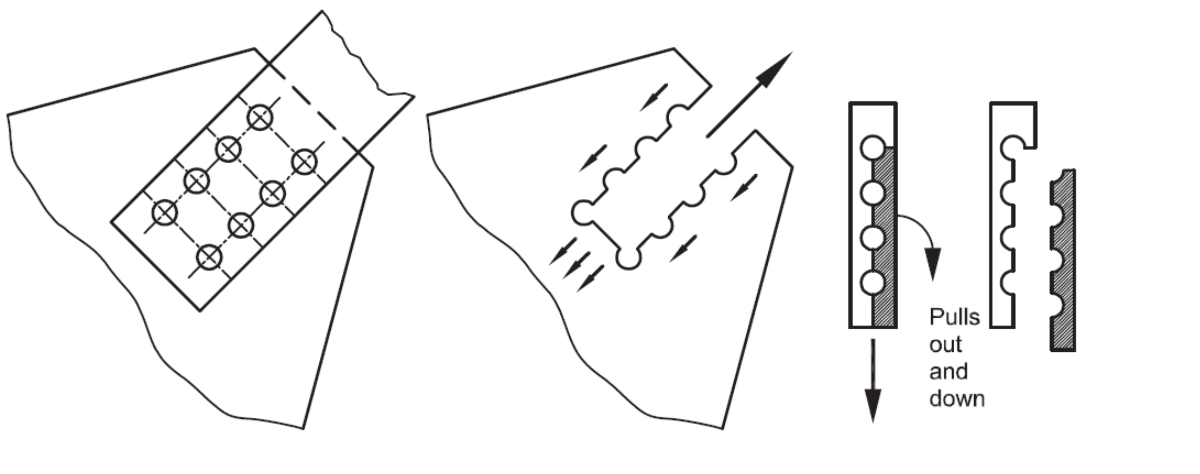
SUMMARY

Block shear failure involves the rupture of a block of material in a bolted steel connection (Key, 2015). NZS 3404 Steel Structures Standard does not contain block shear provisions. This deficiency will be addressed in the current NZS 3404 revision process. This paper examines the mechanisms for block shear failures of bolted connections and summarises the block shear design models presented in international steel standards and research papers. Based on this survey of block shear models, recommended block shear standard provisions for inclusion in NZS 3404 are made. Two worked examples are presented in the article. For comparative purposes, block shear design capacities are computed using the recommended block shear design model and current New Zealand and Australian design practice.

INTRODUCTION

Block shear rupture consists of failure in shear at the row of bolts along the shear face of the hole group accompanied by tensile rupture along the line of bolt boles on the tension face of the bolt group. Examples of block shear rupture are given in figure 1. This failure mechanism is not covered in NZS 3404 *Steel Structures Standard.*

This paper reviews various block shear provisions and provides recommended design provisions for inclusion in a revised NZS 3404 based on recent work by (Teh & Deierlein, 2017).



(a) Gusset plate subject to tension

(b) Cleat component subject to shear

Figure 1: Examples of block shear failure in components (Key, 2015)

NOMINAL BLOCK SHEAR RESISTANCE EQUATIONS

Block shear provisions have been provided in many international standards and in New Zealand design guides for a number of years. The block shear design provisions in these standards and guides are not consistent and have changed many times. The differences are related to the interaction of tension and shear behaviour on assumed gross or net yield and rupture planes (Teh & Deierlein, 2017). Generally there has been a presumption of yielding on gross areas and rupture on net areas, where the gross and net areas are A_{gt} and A_{nt} for tension and A_{gv} and A_{nv} for shear, and the corresponding stress limits for yielding and rupture are the tension yield stress, f_y, and ultimate stress, f_u. Gross and net planes are illustrated in figure 2.

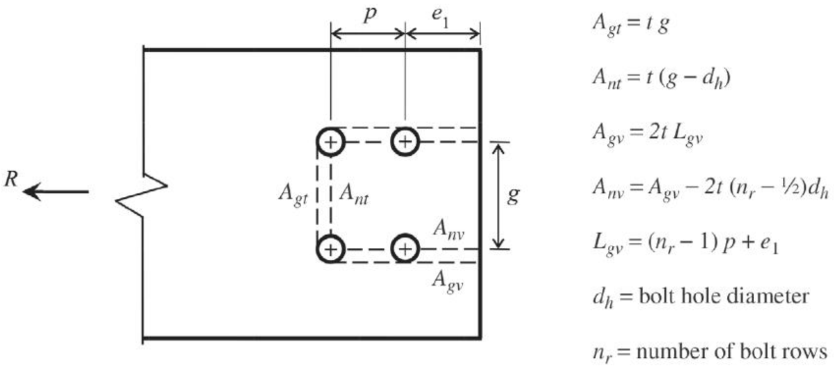


Figure 2: Gross and net planes (Teh & Deierlein, 2017)

Table 1 displays the nominal block shear resistance equations from various international standards and the Steel Construction New Zealand (SCNZ) *Steel Connect* design guide (Hyland, Cowie, Clifton, 2007). The non-uniform stress distribution factor is not shown for the equations in the table, this is discussed in a later section below. The international standards included are the American Institute of Steel Construction (AISC) Specification (AISC, 2016), Australian Standard AS4100 (SA, 2020), Canadian Steel Standard (CSA, 2014), the Eurocode (ECS, 2005) and the Japanese AIJ standard (AIJ, 2002).

Table 1: International standards and SCNZ Steel Connect Nominal Block Shear Capacity. Non-uniform stress distribution factor not included. Modified from (Teh & Deierlein, 2017)

Standard	Nominal Block Shear Equation
AISC	$R_{bs} = min(f_u A_{nt} + 0.6 f_u A_{nv}; f_u A_{nt} + 0.6 f_y A_{gv})$
AS4100	$R_{bs} = min(f_u A_{nt} + 0.6 f_u A_{nv}; f_u A_{nt} + 0.6 f_y A_{gv})$
CSA	$R_{bs} = f_u A_{nt} + 0.6 \frac{f_y + f_u}{2} A_{gv}$
Eurocode	$R_{bs} = f_u A_{nt} + \frac{f_u A_{nv}}{\sqrt{3}}$
AIJ	$R_{bs} = f_u A_{nt} + 0.5 f_y A_{gv}$
Steel Connect	$R_{bs} = max(f_u A_{nt} + 0.6 f_y A_{gv}; f_y A_{gt} + 0.6 f_u A_{nv})$

The AISC design block shear provisions have changed many times as shown in Table 2. The current AISC block shear design provision is the minimum of two equations (1a) and (1b). Both equations use the tensile rupture of the net area. The shear failure is based on shear yielding of the gross area for the first equation and shear rupture of the net for the second equation.

$$R_{bs} = f_u A_{nt} + 0.6 f_y A_{gv} \quad (1a)$$

$$R_{bs} = f_u A_{nt} + 0.6 f_u A_{nv} \quad (1b)$$

(AISC, 2016) block shear design provision often reduces to the second equation for modern structural steels, where the ratio of tensile strength f_u to yield stress f_y is not particularly high.

AS4100 block shear provisions are identical to the current AISC Specifications. The provisions are found in Clause 9.1.9 of AS4100.

The Eurocode block shear design equation (ECS, 2005) uses the von Mises coefficient ($1 / \sqrt{3} = 0.577$) in conjunction with shear yielding along the net shear planes.

$$R_{bs} = f_u A_{nt} + \frac{f_u A_{nv}}{\sqrt{3}} \tag{2}$$

The block shear equation in the Canadian standard (CSA, 2014) is essentially the same as that originally proposed by Huns et al. (2002), which assumes partial strain hardening along the gross shear planes, except that the von Mises shear coefficient ($1 / \sqrt{3} = 0.577$) is replaced by 0.6 in the standard.

$$R_{bs} = f_u A_{nt} + 0.6 \frac{f_y + f_u}{2} A_{gv} \tag{3}$$

The Japanese AIJ nominal block shear equation assumes yielding along the gross shear planes with a reduced shear coefficient of 0.5.

$$R_{bs} = f_u A_{nt} + 0.5 f_y A_{gv} \tag{4}$$

The SCNZ *Steel Connect* nominal block shear provisions take the larger of two equations. The first equation (5a) is identical to current AISC first equation (1a) which uses the tensile rupture of the net area and the shear failure is based on shear yielding of the gross area. The second equation (5b) uses tensile yield of the gross area and the shear failure is based on shear rupture of the net area.

$$R_{bs} = f_u A_{nt} + 0.6 f_y A_{gv} \tag{5a}$$

$$R_{bs} = f_y A_{gt} + 0.6 f_u A_{nv} \tag{5b}$$

The origins of the block shear provisions in Steel Connect can be traced back to 1986 AISC LRFD.

Teh and Deierlin (2017) describe two fundamental problems with the 1986 block shear provision (AISC, 1986). First, contrary to its intention of adopting a more conservative model, it often results in a less conservative design against the block shear failure mode compared to the original equation (AISC, 1978). Second, its prescription that "the controlling equation is one that produces the larger force" is contrary to well established design conventions of choosing the lowest of multiple possible failure modes.

Table 2: AISC Specification Block Shear Design Provisions, 1978-2016. Modified from (Teh & Deierlein, 2017)

Year	Block Shear Design Provision
1978	$R_{bs} = f_{uc} A_{nt} + 0.6 f_{uc} A_{nv}$
1986	$R_{bs} = max(f_{uc} A_{nt} + 0.6 f_{yc} A_{gv}; f_{yc} A_{gt} + 0.6 f_{uc} A_{nv})$
1993	$if\ f_{uc} A_{nt} \geq 0.6 f_{uc} A_{nv}: R_{bs} = f_{uc} A_{nt} + 0.6 f_{yc} A_{gv}$ $if\ f_{uc} A_{nt} < 0.6 f_{uc} A_{nv}: R_{bs} = f_{yc} A_{gt} + 0.6 f_{uc} A_{nv}$
1999	$if\ f_{uc} A_{nt} \geq 0.6 f_{uc} A_{nv}: R_{bs} = min(f_{uc} A_{nt} + 0.6 f_{uc} A_{nv}; f_{uc} A_{nt} + 0.6 f_{yc} A_{gv})$ $if\ f_{uc} A_{nt} < 0.6 f_{uc} A_{nv}: R_{bs} = min(f_{uc} A_{nt} + 0.6 f_{uc} A_{nv}; f_{yc} A_{gt} + 0.6 f_{uc} A_{nv})$
2005 2010 2016	$R_{bs} = min(f_{uc} A_{nt} + 0.6 f_{uc} A_{nv}; f_{uc} A_{nt} + 0.6 f_{yc} A_{gv})$

PROPOSED NEW BLOCK SHEAR EQUATION

(Teh & Deierlein, 2017) have recently proposed a new block shear equation. The shear failure planes are taken to be neither the assumed net nor gross shear planes, but rather effective shear planes with a calculated area that is the mean between the net and gross areas. The equation assumes full strain hardening (plastic flow stress of $0.6f_u$) along the effective shear planes, up to the point of tensile fracture on the net tension plane. Failure planes are shown in figure 3.

$$R_{bs} = f_u A_{nt} + 0.6 f_u A_{ev} \quad (6)$$

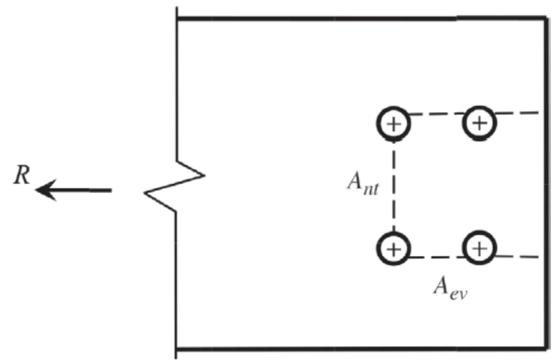


Figure 3: Net tenson and effective shear failure planes for proposed block shear model (Teh & Deierlein, 2017)

The proposed equation is consistent with observed deformations and failure modes in shear tearout tests of bolted connections which suggest that the effective shear failure plane lies midway between the net and the gross shear planes. An example of this is the failure mode shown in Figure 4 for the downstream bolt of a serial bolted connection tested by Cai and Driver (2010).

Figure 4: A downstream bolt failure in shear tearout (Cai and Driver, 2010)

The proposed equation is based on earlier work by Teh and Uz (2015) which have pointed out that shear yielding in a block shear failure is typically accompanied by full strain hardening ($0.6f_u$) (Teh & Deierlein, 2017). There is large ductility of steel in shear. Steel in the shear yielding zone can strain harden up to f_u and sustain large strains without the necking and rupture behaviour that occurs in standard tensile coupons.

COMPARISON OF BLOCK SHEAR EQUATIONS WITH TEST DATA

Strengths calculated using the proposed block shear equation and the current AISC provision (AISC, 2016) are compared by (Teh & Deierlein, 2017) to previously published test data. This is shown in Table 3. The table covers 155 tests by 11 independent research teams. All the specimens in the table failed in a conventional block shear mode along the failure planes as illustrated in Figure 3.

It can be seen from Table 3 that strengths calculated by the proposed equation are consistently accurate across reported tests, where the overall mean professional factor (P_t/R_n, ultimate test load/computed strength using the design model) of 1.01 has a 5% coefficient of variation. In contrast, the current AISC equation (AISC, 2016) has an overall mean professional factor of 1.18. Thus, the AISC provision is conservative by about 20%.

Table 3: Comparison between test data and strength calculated by the proposed equation and AISC block shear equations (Teh & Deierlein, 2017)

	N	n_{rmax}	n_{1max}	d_h, (mm)	F_u/F_y	$P_t/(F_uA_{nt})$	Mean P_t/R_n	
							AISC	Proposed
Hardash and Bjorhovde (1985)	28	5	2	14–17	1.30–1.41	2.2–6.7	1.20	1.03
Rabinovitch and Cheng (1993)	5	5	2	22	1.20	7.5–8.5	1.17	0.99
Udagawa and Yamada (1998)	72	4	4	18	1.08–1.70	1.7–6.0	1.18	0.99
Aalberg and Larsen (1999)	8	4	2	19	1.05–1.44	4.0–7.1	1.20	0.99
Menzemer et al. (1999)	20	7	2	17.5	1.12	3.7–14.0	1.16	1.00
Nast et al. (1999)	3	5	2	22	1.17	8.2–8.5	1.23	1.04
Swanson and Leon (2000)	1	4	2	24	1.33	4.1	1.30	1.05
Puthli and Fleischer (2001)	6	1	2	30	1.23	2.1–2.4	1.18	1.01
Huns et al. (2002)	5	3	4	21	1.34	2.6–8.0	1.26	1.08
Mullin (2002)	5	8	2	21	1.37	2.6–7.8	1.14	1.00
Moze and Beg (2014)	2	1	2	22	1.36	2.3–3.1	1.24	1.08
						Overall mean	1.18	1.01
						COV	0.051	0.048

Note: 1 in. = 25.4 mm

(Teh & Deierlein, 2017) also compared the Canadian, European and AIJ nominal block shear equations against test data. This is presented in Table 4 for test data from (Puthli and Fleischer, 2001) and Table 5 for test data from (Aalberg and Larson, 1999). The Canadian standard equation leads to overestimations as large as 10%, depending on the geometry. The Eurocode's equation was found to be often excessively conservative (28 – 65%).

The Japanese AIJ model (AIJ, 2002) is the most accurate for the results shown in Table 4, where it is only about 10% conservative as compared to the unconservative Canadian model (CSA, 2014) and the 20 to 30% conservatism in the AISC (AISC, 2016) and European (ECS, 2005) models.

However, the AIJ model has been found by (Teh & Deierlein, 2017) to be quite conservative in most cases. In addition to the first four specimens listed in Table 5, the AIJ equation is 30% or more for many of the specimens tested by Udagawa and Yamada (1998), Huns et al. (2002), Mullin (2002), and Moze and Beg (2014).

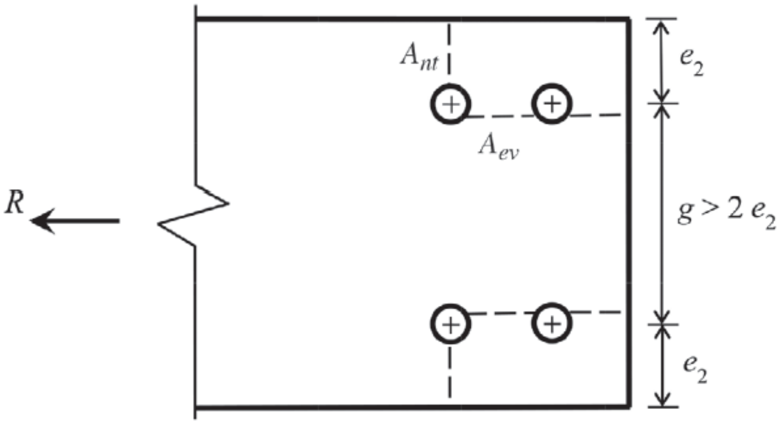


Figure 5: Split block shear failure planes (Teh & Deierlein, 2017)

Table 4: (Teh & Deierlein, 2017) comparison of model equations for tests by (Puthli and Fleischer, 2001) that failed in both conventional (C) and Split (S) Block Shear

Specimen	*g*, (mm)	e_2, (mm)	Mode	P_t/R_n				
				AISC	Eq. (6)	CSA	ECS	AIJ
12	54	36	C	1.16	0.98	0.90	1.28	1.07
13	—	40.5	—	1.16	0.98	0.90	1.28	1.07
14	—	45	—	1.19	1.01	0.93	1.32	1.10
17	63	36	—	1.19	1.03	0.96	1.29	1.11
18	—	40.5	—	1.21	1.05	0.97	1.32	1.13
19	—	45	—	1.19	1.03	0.96	1.30	1.11
20	72	27	S	1.23	1.04	0.96	1.36	1.14
21	—	31.5	—	1.21	1.05	0.97	1.31	1.13
22	81	27	—	1.18	1.00	0.92	1.31	1.09
23	—	31.5	—	1.19	1.03	0.96	1.29	1.11
24	90	27	—	1.20	1.01	0.93	1.33	1.11
25	—	31.5	—	1.19	1.03	0.96	1.30	1.12
Puthli and Fleischer (2001)			Mean	1.19	1.02	0.94	1.31	1.11
			COV	0.017	0.023	0.027	0.017	0.019

Note: Proposed equation = Eq. (6)

Table 5: (Teh & Deierlein, 2017) comparison of block shear equations for tests by (Aalberg and Larson, 1999)

Table A-1. Effects of Assumptions and Approximations in Block Shear Equations

Specimens	F_y, (MPa)	F_u, (MPa)	*t*, (mm)	n_r	P_t/R_n				
					Eq. (1a)	Eq. (6)	CSA	ECS	AIJ
T7	373	537	8.4	2	1.21	1.06	1.05	1.59	1.38
T9	—	—	—	3	1.18	1.03	1.01	1.65	1.36
T11	—	—	—	4	1.13	0.99	0.96	1.64	1.32
T15	—	—	—	3	1.12	0.98	0.95	1.56	1.29
T8	786	822	7.7	2	0.90	1.00	0.89	1.21	1.04
T10	—	—	—	3	0.86	0.97	0.84	1.22	1.00
T12	—	—	—	4	0.82	0.94	0.80	1.20	0.96
T16	—	—	—	3	0.83	0.94	0.82	1.18	0.97
Aalberg and Larsen (1999)				Mean	1.01	0.99	0.91	1.41	1.16
				COV	0.169	0.043	0.100	0.154	0.163

Note: d_h = 19 mm; e_1 = 38 mm; p = 48 mm; g = 48 mm

Note: Proposed equation = Eq. (6), AISC(2016) Equation 1a = Eq. (1a)

ADOPTION OF PROPOSED EQUATION IN INTERNATIONAL STANDARDS

The proposed equation is currently not codified in any structural steel standards, it is however understood being considered for inclusion in two international standards. The recommended equation has been included in the 2018 edition of AS/NZS 4600 (SA/SNZ, 2018).

ECCENTRIC LOADING AND NON-UNIFORM TENSION STRESS

Current international standards apply a nonuniform stress distribution factor, denoted k_{bs} in the Australian standard, to the tensile strength component, f_uA_{nt}, of the block shear resistance. This reduction factor is equal to unity in most cases, including a concentrically loaded gusset plate. A double line bolted coped beam shear connection is considered to result in non-uniform (k_{bs} = 0.5) tensile stress distribution.

(Teh & Deierlein, 2017) found the non-uniform stress contribution factor conservative for a double line bolted coped beam shear connection. However due to the limited verification test results did not propose changes to the current non-uniform stress distribution factor.

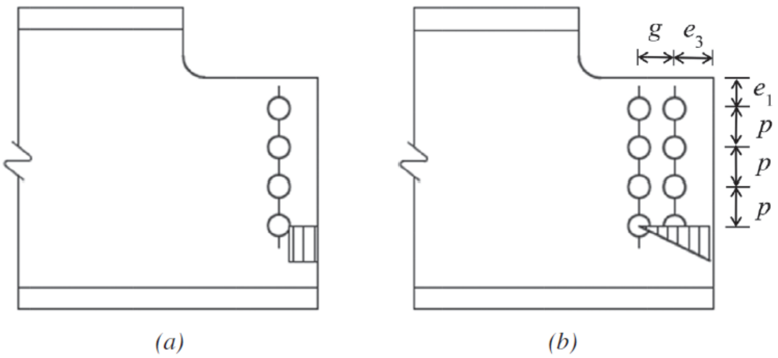


Figure 6: AISC tensule stress distribution factor: (a) k_{bs} = 1.0; (b) k_{bs} = 0.5 (AISC. 2016)

CAPACITY REDUCTION FACTOR

AISC (2016) and AS4100 (2016) use a capacity factor of 0.75. Previous Australian and NZ design guidance used a capacity factor of 0.9 while also acknowledging that the US capacity factor for the same block shear provisions used is 0.75.

(Teh & Deierlein, 2017) carried out a reliability analysis on the proposed equation and recommended a capacity reduction factor equal to 0.85. The reliability analysis methodology and the statistical parameters were adopted from Driver et al. (2006),

PROPOSED NZS 3404 BLOCK SHEAR PROVISIONS

The authors recommend that the proposed equation by (Teh & Deierlein, 2017) be adopted for NZS 3404. This equation gives the most accurate result compared with test data and is conceptually simple to understand. The capacity factor recommended by (Teh & Deierlein, 2017) is also recommended. The eccentric loading and non-uniform stress distribution factor as used in AS4100 is also recommended to be applied. To be in keeping with AS4100 block shear provisions the proposed block shear clause is as follows:

9.1.1X Design for Block Shear Rupture

Block shear rupture consists of failure in shear at the row of bolts along the shear face of the hole group accompanied by tensile rupture along the line of bolt boles on the tension face of the bolt group. Figure 7 shows two examples of block shear rupture.

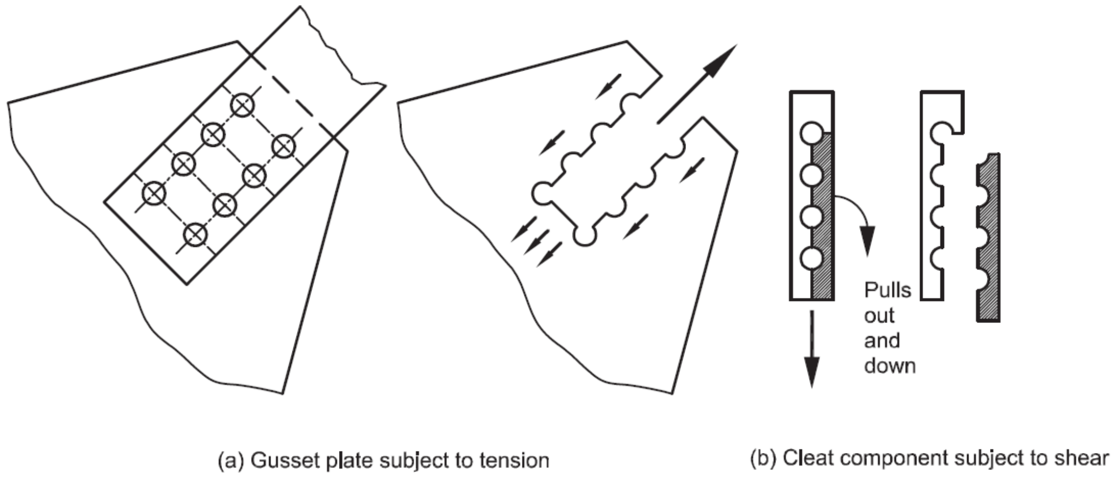


Figure 7: Examples of Block Shear Rupture in Components (Key, 2015)

A connection component, including a member framing onto the connection component, subject to a design shear force or design tension force (R^*_{bs}) shall satisfy:

$$R^*_{bs} \leq \phi R_{bs}$$

where

ϕ	= capacity factor
	= 0.85
R_{bs}	= nominal design capacity in block shear
	= $k_{bs} f_{uc} A_{nt} + 0.6 f_{uc} A_{ev}$
f_{uc}	= minimum tensile strength of connection element
f_{yc}	= yield stress of connection element
A_{nv}	= net area subject to shear at rupture
A_{nt}	= net area subject to tension at rupture
A_{gv}	= gross area subject to shear at rupture
A_{ev}	= effective area subject to shear at rupture
	= $\frac{A_{gv}+A_{nv}}{2}$
k_{bs}	= a factor to account for the effect of eccentricity on the block shear capacity
	= 1.0 when tension stress is uniform
	= 0.5 when tension is non-uniform

COMPARISON OF DESIGN BLOCK SHEAR CAPACITY IN TWO EXAMPLES

<u>Example 1</u>

The first comparison example is taken from (Key, 2015). For this example the design capacity of the cleat plate in block shear as shown in figure 8 is computed. Two modes of block shear failure are applicable. The first mode involves tearing along the direction of the force and the second mode involves tear out across to one side of the cleat. The inputs in the block shear equations are as follows:

$f_y = 350\ MPa$

$f_u = 430\ MPa$

$A_{nv} = 1440\ mm^2$ for Mode A

$A_{nv} = 720\ mm^2$ for Mode B

$A_{nt} = 960\ mm^2$ for Mode A
$A_{nt} = 1200\ mm^2$ for ModeB
$A_{gv} = 2100\ mm^2$ for Mode A
$A_{gv} = 1050\ mm^2$ for Mode B

The design capacity of the cleat plate in block shear is computed using the AS4100 and current AISC block provisions, the SCNZ Steel Connect block provision and the proposed equation for NZS 3404.

AS4100 and AISC:
$\varphi R_{bs} = 0.75\ x\ min(f_u A_{nt} + 0.6 f_u A_{nv}; f_u A_{nt} + 0.6 f_y A_{gv}) = 539\ kN\ \ Mode\ A\ governs$

SCNZ Steel Connect:
$\varphi R_{bs} = 0.9\ x\ max(f_u A_{nt} + 0.6 f_y A_{gv}; f_y A_{gt} + 0.6 f_u A_{nv}) = 675\ kN\ Mode\ B\ governs$

Proposed for NZS 3404:
$\varphi R_{bs} = 0.85\ x\ k_{bs} f_{uc} A_{nt} + 0.6 f_{uc} A_{ev} = 647\ kN\ Mode\ B\ governs$

In this example the proposed equation gives a higher capacity value then AS4100 and AISC block shear equations and is within 4% of the SCNZ Steel Connect capacity value.

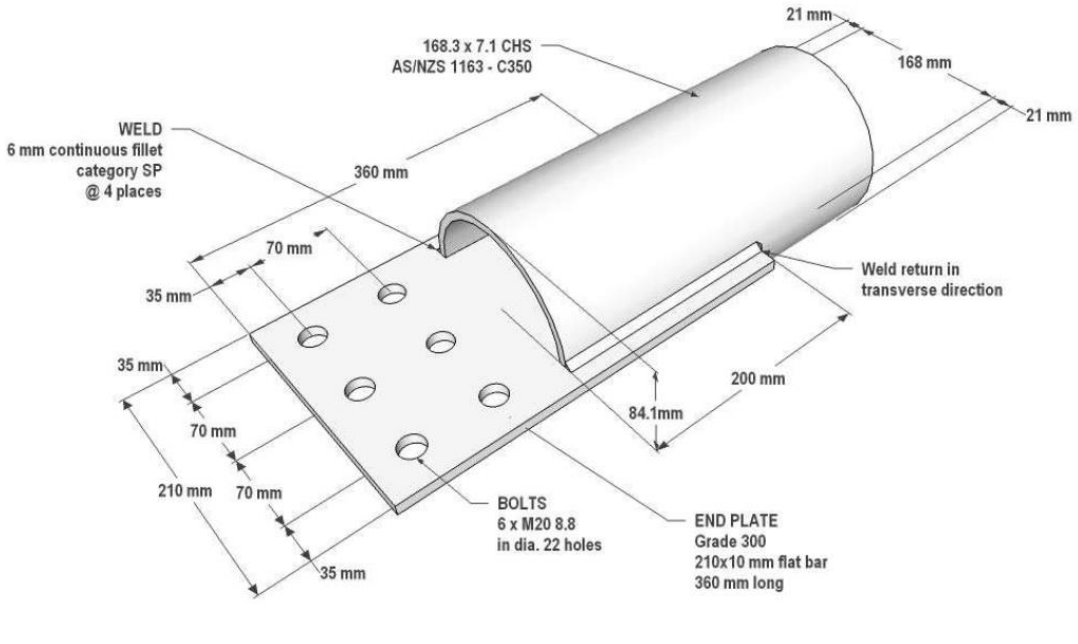


Figure 8: Example 1 (Key, 2015)

<u>Example 2</u>
The second comparison example is taken from (Teh & Deierlein, 2017). The connection details is shown in figure 9. The number of bolts rows shown is four. However for this example the design capacity of the gusset plate in block shear is computed for three bolt rows. The equivalent metric inputs in the block shear equations are as follows:

$f_y = 50\ ksi =\ 345\ MPa$
$f_u = 65\ ksi =\ 448\ MPa$
$R_u = 270\ kips =\ 1201\ kN$
$Bolt\ diameter = 0.75\ in = 19\ mm$
$Bolt\ pitch\ and\ gauge = p = g = 2.5\ in = 63.5mm$
$Bolt\ edge\ distance =\ e_1 = 1.5\ in = 38.1\ mm$

$$Nominal\ bolt\ hole\ diameter = \frac{13}{16} in = 20.6mm$$
$$Maximum\ bolt\ hole\ diameter = \frac{13}{16} + \frac{1}{16} = \frac{14}{166} in = 22.2mm$$
$$Number\ of\ bolt\ rows = n_r = 3$$
$$Gusset\ thickness = \frac{5}{8} in = 15.9\ mm$$
$$A_{nt} = 1.02\ in^2 = 655\ mm^2$$
$$A_{gv} = 8.125\ in^2 = 5241\ mm^2$$
$$A_{nv} = 5.39\ in^2 = 3478\ mm^2$$

The design capacity of the gusset plate in block shear is computed using the AS4100 and current AISC block provisions, the SCNZ Steel Connect block provision and the proposed equation for NZS 3404.

AS4100 and AISC:
$$\varphi R_{bs} = 0.75\ x\ min(f_u A_{nt} + 0.6 f_u A_{nv}; f_u A_{nt} + 0.6 f_y A_{gv}) = 921\ kN$$

SCNZ Steel Connect:
$$\varphi R_{bs} = 0.9\ x\ max(f_u A_{nt} + 0.6 f_y A_{gv}; f_y A_{gt} + 0.6 f_u A_{nv}) = 1241\ kN$$

Proposed for NZS 3404:
$$\varphi R_{bs} = 0.85\ x\ k_{bs} f_{uc} A_{nt} + 0.6 f_{uc} A_{ev} = 1246\ kN$$

In this example the proposed equation gives a higher capacity value then AS4100 and AISC block shear equations and is slightly higher then the SCNZ Steel Connect capacity value.

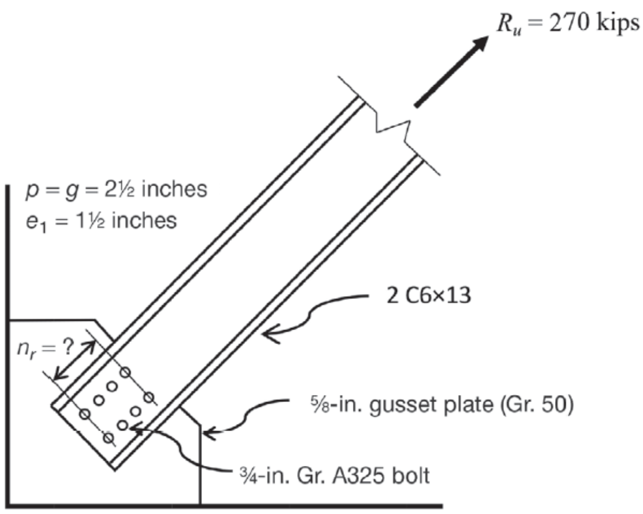


Figure 9: Block shear deisgn example 2 (Teh & Deierlein, 2017)

CONCLUSION

The proposed block shear equation in (Teh & Deierlein, 2017) is recommended for inclusion into the next revision of NZS 3404. The proposed design provisions are more accurate than the current block provisions in AS4100 and provide greater capacity and provide roughly the same level as past NZ guidance on block shear.

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