Bearing Design of Thin Sheet Steel Screwed Connections

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SUMMARY

The 1996 Australian / New Zealand AS/NZS 4600 and North American; CSA-S136, AISI Cold Formed Steel Design Standards allow for the use of thin (t < 0.9 mm in AS/NZS 4600), high strength (f_y = 550 MPa) sheet steels if the yield stress and ultimate strength are reduced to 75% of their minimum specified values. At present, these reduced material properties must be used in the design of screwed connections which undergo bearing and bearing/tilting failure. Previous research has illustrated the need for design standards to include a gradated bearing coefficient method to account for the behaviour of thin high strength sheet steels, instead of a gross reduction in material properties. This paper provides a summary of results detailing the behaviour of screwed connections tested in shear which have failed in the bearing and bearing/tilting modes. Recommendations concerning the adequacy of current design standards with respect to a proposed formulation which can be used to more accurately predict the shear resistance of screwed connections which fail in the bearing and bearing/tilting modes are presented.

1 INTRODUCTION

Cold formed structural members are fabricated from sheet steels consisting of various material properties which must meet the requirements prescribed in applicable national design standards. The Australian / New Zealand Standard for cold formed steel structures AS/NZS 4600 *(SA/SNZ, 1996)* allows for the use of thin (t < 0.9 mm), high strength (f_y = 550 MPa) sheet steels in all structural sections. However, due to the low ductility exhibited by sheet steels which are cold reduced to thickness the engineer must use a yield stress and ultimate strength limited to 75% of the minimum specified values. The American Iron and Steel Institute (AISI) Design Specification *(AISI, 1997a)* further limits the use of thin, high strength steels to roofing, siding and floor decking panels. Sheet steels are required to have a minimum elongation capability to ensure that members and connections can undergo small displacements without a loss in structural performance, and to reduce the harmful effects of stress concentrations. The ductility criterion specified in the Australian / New Zealand and North American Design Standards *(CSA, 1994; AISI, 1997a)* is based on an investigation of sheet steels by Dhalla and Winter *(1974a,b)* which did not include the thin, high strength G550 sheet steels available today. The G550 sheet steels used for this research must be differentiated from other sheet steels whose high yield stress and ultimate strength values are obtained by means of an alloying process, i.e. high strength low alloy (HSLA) steels. Note: An earlier paper by Rogers and Hancock *(1997a)* provides information on the ductility of G550 and G300 sheet steels as used for the tests discussed in this paper. More detailed information on these screwed connection tests of thin G550 and G300 sheet steels can be found in Rogers and Hancock *(1997b)*. Rogers and Hancock recommended that the bearing coefficient for single overlap screwed connections contained in the Australian / New Zealand *(SA/SNZ, 1996)* and USA *(AISI, 1997a)*

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Design Standards is unconservative for thin sheet steels and test results warrant that a gradated bearing coefficient be used in design.

This paper reports on a proposed modification to the existing design formulation for single overlap screwed connections loaded in shear. A gradated bearing coefficient method is evaluated and calibrated using the test results of single overlap screwed connections concentrically loaded in shear, and fabricated using G550 and G300 sheet steels (see AS 1397 *(1993)*). Sheet steels which range in base metal thickness from 0.42-2.94 mm were included, where the type, number and orientation of screws were varied. The results of additional screwed connection specimens, mainly composed of single point fasteners, which were tested by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Building, Construction and Engineering *(Macindoe and Pham, 1995, 1996)*, are also included as data for this paper.

2 Cold Formed Steel Screwed Connection Design Provisions

An overview of the design equations used for the prediction of bearing, as well as combined bearing/tilting connection capacity is provided in this section. The design bearing capacity per screw for connections regardless of the design standard used is as follows,

$$V_b = C f_u d t \quad (1)$$

where C is a variable bearing coefficient. The Australian / New Zealand *(SA/SNZ, 1996)* and USA *(AISI, 1997a)* Design Standards require that $C = 2.7$ for shear connections, whereas the European Design Standard *(Eurocode, 1996)* requires that $C = 2.1$. In the Canadian Design Standard *(CSA, 1994)* C represents the stability of the hole edge based on the ratio of screw diameter to sheet

Table 1 Factor C, for Bearing Resistance ***(CSA, 1994)***

d/t	C
$d/t \leq 10$	3
$10 < d/t < 15$	$30\ t/d$
$d/t \geq 15$	2

thickness, as listed in Table 1. The Australian / New Zealand and USA Design Standards specify that for a single shear connection where $t_2 / t_1 \leq 1.0$ and the two sheets are in contact at the screw position, the nominal bearing capacity is taken as the smaller of (2)-(4).

$$V_b = 4.2\sqrt{(t_2^3 d)}f_{u2} \quad (2)$$

$$V_b = 2.7 t_1 d f_{u1} \quad (3)$$

$$V_b = 2.7 t_2 d f_{u2} \quad (4)$$

where (2) is a tilting formulation, t_1 and f_{u1} are the thickness and ultimate strength of the member in contact with the screw head, and t_2 and f_{u2} are the thickness and ultimate strength of the member not in contact with the screw head.

For a single shear connection where $t_2 / t_1 \geq 2.5$ and the two sheets are in contact at the screw position, the nominal bearing capacity is taken as the smaller of the following:

$$V_b = 2.7 t_1 d f_{u1} \quad (5)$$

$$V_b = 2.7 t_2 d f_{u2} \quad (6)$$

For a screw connection where $1.0 < t_2 / t_1 < 2.5$ and the two sheets are in contact at the screw position, the nominal bearing capacity is calculated from a linear interpolation between the minimum value obtained from (2)-(4) and the minimum value obtained from (5) and (6). Only the Australian / New Zealand *(SA/SNZ, 1996)* and USA *(AISI, 1997a)* Design Standards allow for screwed connections where the thinner material is not in contact with the head of the screw.

The Canadian Design Standard *(CSA, 1994)* provides an alternative formula to predict the nominal tilting resistance based on the combined thickness of the connected sheets, where the thinner material, t_1, is assumed to be in contact with the head of the screw.

$$B_r = C\,(t_1 + t_2)\,d\,f_{u1} / 4 \tag{7}$$

The European Design Standard *(Eurocode, 1996)* includes a combined formulation of bearing and tilting where the thinner material, t_1, is also assumed to be in contact with the head of the screw. This differs from the Australian / New Zealand *(SA/SNZ, 1996)* and USA *(AISI, 1997a)* Design Standards where the material which is not in contact with the head of the screw, t_2, is used in the tilting formula (see (2)).

$$F_{b,Rd} = \alpha f_u\, d\, t_1 \tag{8}$$

where α is defined as follows;

$$\text{if } t_1 = t_2 \qquad \alpha = 3.2\sqrt{t_1/d} \le 2.1 \tag{9}$$

$$\text{if } t_2 \ge 2.5\,t_1 \qquad \alpha = 2.1 \tag{10}$$

If $t_1 < t_2 \le 2.5\,t_1$ then α is obtained by linear interpolation between (9) and (10).

3 Screwed Connection Test Specimens

3.1 General

The results of screwed connection tests by Rogers and Hancock *(1997b)*, as well as by Macindoe and Pham *(1995, 1996)* have been used as a basis for comparison between the current design equations specified in the Australian / New Zealand *(SA/SNZ, 1996)*, North American *(CSA, 1994; AISI, 1997a)* and European *(Eurocode, 1996)* Cold Formed Steel Design Standards, as well as the proposed bearing formulation. The ultimate load, P_{ut}, and serviceability based loads, i.e. the maximum load at/or before a connection displacement of 3 mm, $P_{3.0t}$, specified in ECCS TC7 *(1983)*, and a connection displacement of 6.35 mm, $P_{6.35t}$, specified by the Research Council on Structural Connections *(AISC, 1988)* and the American Institute of Steel Construction *(1989, 1993)* (see Rogers and Hancock *(1997b)*) were used in the comparison with predicted loads.

3.2 Rogers and Hancock

One hundred and fifty single overlap screwed connection specimens with multiple point fasteners were tested in shear at the University of Sydney. Five different sheet steels were used, including both G550 and G300 grades which ranged in base metal thickness from 0.42–1.00 mm. Connections were tested with various type, number and arrangement of screws. Eight types of HITEKS and STITCH screws were used for this project. Further information concerning the types of screw connection specimens, test procedures and detailed results for the data contained in this paper can be found in Rogers and Hancock *(1997b)*.

3.3 CSIRO

The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Building, Construction and Engineering completed a series of reports on the performance of single point fasteners used with light gauge sheet steel connections *(Macindoe and Pham, 1995, 1996)*. A limited amount of test data from the CSIRO study was included in this paper to provide a comprehensive listing of available single overlap screwed connection tests composed of G550 sheet steels. This data does not consist of all screwed tests completed by the CSIRO, only those which can be used to further understand the bearing and tilting behaviour of G550 sheet steels in shear connections. Of the 158 additional single overlap screw tests which were listed as having failed by either bearing or tilting, 146 were solely composed of G550 sheet steels and 12 were composed of a thinner G550 sheet steel with a thicker G250 sheet steel. For all additional tests the thinner sheet steel was placed adjacent to the screw head.

3.4 Possible Modes of Failure

Various modes of failure can occur in a single overlap screwed sheet steel connection including; gross cross-section yielding, net cross-section fracture, end pull-out, bearing, tilting, combined bearing/tilting and screw shear. Only connections which failed by bearing or combined bearing/tilting (see Fig. 1) were included as data for this paper. In a bearing failure, the screws remain perpendicular to the sheet steel and an initial pull out tear in the direction of load, with piling of the sheet steel in front of the screw is exhibited. Typically, sheet distortion occurs to a greater extent in the thinner material. The mode of failure recorded for all but 12 of the screw

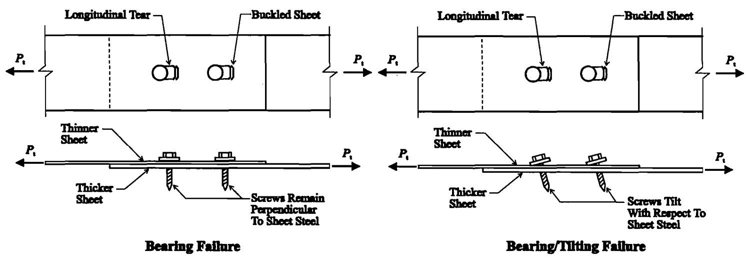


Fig. 1 Bearing and Bearing/Tilting Failure Patterns

connection tests included was a combination of bearing and tilting, due to; 1) the extreme thinness of the sheet steels used, and in some cases 2) the use of screw fasteners for which the threads do not extend up to the base of the screw head, i.e. a non-threaded shank is located directly below the screw head due to limitations in the manufacturing process. In the bearing/tilting failure mode the ultimate load is preceded by a tearing of the sheet steel in the direction of load with the associated piling of sheet steel in front of the fasteners, along with a tilting of the screws caused by the eccentric loading of the two sheets. Failure is caused by a build-up of axial tensile forces in the screw and bearing stresses in the sheet steel. The tilting forces result from the rotated position of the fastener with respect to the direction of load in the connection.

4 PROPOSED DESIGN PROVISIONS FOR SCREWED CONNECTIONS

4.1 Basis of the Proposed Method

A proposed method to accommodate for the change in bearing behaviour with sheet steel thickness, which relies on the ratio of screw diameter to sheet thickness, *d/t*, is presented in this section. Significantly unconservative predictions of connection resistance obtained for certain test specimens have demonstrated a need for a variable bearing coefficient which is dependent on the stability of the edge of the screw hole. Unconservative predictions of connection capacity have been recorded for test specimens where two different thickness sheet steels are connected and loaded in shear, as shown for the test-to-predicted results calculated using the AS/NZS 4600 *(1996)* and AISI *(1997a)* Design Standards for the 042/060-G550 and 042/100-G550 tests, the 042/080-G550 and 042/100-G550 tests, as well as the 042-G550/294-G250 tests (Note: 042/060-G550 refers to a connection composed of a 0.42 mm G550 sheet steel placed adjacent to the screw head and a 0.60 mm G550 sheet steel attached below. When a connection specimen was composed of two different thickness sheet steels, the thinner sheet steel was placed adjacent to the screw head.) The screwed connection test specimens included in this paper which have two elements of the same thickness, all failed in a combined bearing/tilting mode and have acceptable test-to-predicted ratios (see Rogers and Hancock *(1997b)*).

Macindoe and Pham *(1996)* tested a number of screwed connections where bearing failure was forced to occur because of a large differential in the thickness of the connected sheets, e.g., 042-G550/294-G250 tests. This behaviour differs from that exhibited for the majority of connections tested for this paper and by Macindoe and Pham, where failure was due to a combination of bearing and tilting. The connection resistance calculated for the screwed connection tests where bearing/tiling failure occurred is reasonably accurate. Hence, this proposed method includes the tilting formulation specified in both the AS/NZS-4600 *(1996)* and AISI *(1997a)* Design Standards. It also includes the gross yielding and net section fracture failure provisions contained in the CSA-S136 (1994) and Eurocode 3 (1996) Design Standards, i.e., no stress reduction factor is used (see Rogers and Hancock *(1997b)*).

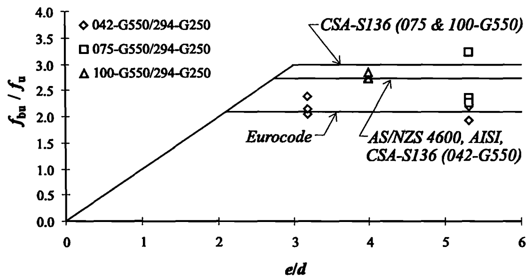


Fig. 2 Bearing Stress Ratios for CSIRO Pure Bearing Failure Specimens *(Macindoe and Pham, 1996)*

Modification to the existing screwed connection design provision was made to the bearing and bearing/tilting formulation. Bearing stress ratios, f_{bu} / f_u, for the CSIRO *(Macindoe and Pham, 1996)* test specimens which failed by pure bearing are provided in Fig. 2 and Table 2. These test specimens consist of two separate thickness sheet steels for which bearing failure occurred in the thinner of the connected elements, i.e., the 042-G550, 075-G550 and 100-G550 sheet steels. The bearing stress ratios for these specimens decrease as the thickness decreases. Hence, a formulation to calculate a bearing coefficient which is similar to that recommended in the CSA-S136 Design Standard *(1994)* is proposed. The maximum and minimum bearing coefficients are 2.7 and 2.0, respectively, which correspond to the results illustrated in Fig. 2. The calculated bearing stress ratio for test D11 is much higher in comparison to similar tests (see Table 2), hence, this result was not taken into account in the development of the proposed method.

At present, the bearing coefficient contained in the AS/NZS-4600 *(1996)* and AISI *(1997a)* Design Standards is a constant 2.7 for screw connections. The Eurocode Design Standard *(1996)* also specifies a constant bearing coefficient of 2.1 for screwed connections. The CSA-S136 Design Standard *(1994)* requires that the bearing coefficient vary depending on the ratio of *d/t*, as shown in Fig. 3. The proposed method contains a variable bearing coefficient which is also dependent on *d/t*, however, the maximum allowed value is lowered to 2.7 and the rate of change of the bearing coefficient is modified accordingly.

Table 2 Existing and Proposed Bearing Coefficients with CSIRO Bearing Failure Data *(Macindoe and Pham, 1996)*

Specimen	f_{bu}/f_u	*e/d*	*d/t*	*Exist. Bearing Coefficients* CSA-S136	AS/NZS 4600 AISI	Euro-code	*Proposed C Value*
042-G550/294-G250							
D176	1.93	5.31	11.2	2.68	2.7	2.1	2.18
D177	2.19	5.31	11.2	2.68	2.7	2.1	2.18
D178	2.19	5.31	11.2	2.68	2.7	2.1	2.18
D182	2.04	3.18	11.2	2.68	2.7	2.1	2.18
D183	2.14	3.18	11.2	2.68	2.7	2.1	2.18
D184	2.38	3.18	11.2	2.68	2.7	2.1	2.18
075-G550/294-G250							
D12	2.37	5.31	6.28	3.00	2.7	2.1	2.67
D11	3.23	5.31	6.28	3.00	2.7	2.1	2.67
D10	2.27	5.31	6.28	3.00	2.7	2.1	2.67
100-G550/294-G250							
D92	2.74	4.00	6.25	3.00	2.7	2.1	2.68
D91	2.86	4.00	6.25	3.00	2.7	2.1	2.68
D90	2.72	4.00	6.25	3.00	2.7	2.1	2.68

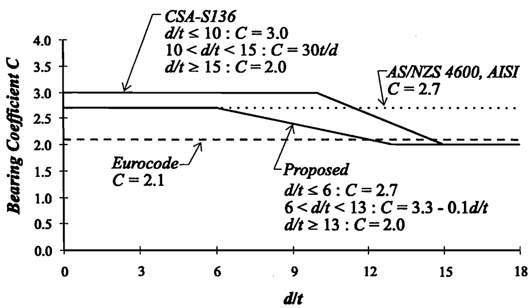


Fig. 3 Existing and Proposed Bearing Coefficients for Screw Connections

The proposed bearing/tilting formulation specifies that for a single shear connection where $t_2 / t_1 = 1.0$ and the two sheets are in contact at the screw position, the nominal bearing capacity is taken as the smaller of (11)-(13).

$$V_b = 4.2\sqrt{(t_2^3 d)}f_{u2} \tag{11}$$

$$V_b = C_1 t_1 d f_{u1} \tag{12}$$

$$V_b = C_2 t_2 d f_{u2} \tag{13}$$

where t_1 and f_{u1} are the thickness and full ultimate strength of the member in contact with the screw head, t_2 and f_{u2} are the thickness and full ultimate strength of the member not in contact with the screw head and C_1 and C_2 are the variable bearing coefficients as presented in Table 3.

Table 3 Proposed Factor *C*, for Bearing Resistance

d/t	C
$d/t \le 6$	2.7
$6 < d/t < 13$	$3.3 - 0.1\, d/t$
$d/t \ge 13$	2.0

For a single shear connection where $t_2 / t_1 \ge 2.5$ and the two sheets are in contact at the screw position, the nominal bearing capacity is taken as the smaller of the following:

$$V_b = C_1 t_1 d f_{u1} \tag{14}$$

$$V_b = C_2 t_2 d f_{u2} \tag{15}$$

For a screw connection where $1.0 < t_2 / t_1 < 2.5$ and the two sheets are in contact at the screw position, the nominal bearing capacity is calculated from a linear interpolation between the minimum value obtained from (11)-(13) and the minimum value obtained from (14) and (15).

4.2 Comparison of the Proposed Method with Existing Design Standards

The proposed design method gives the same predicted connection capacity as calculated using the AS/NZS 4600 *(1996)* and AISI *(1997a)* Design Standards where two sheet steels of the same thickness are joined, based on the range of test specimens included in this paper (see Rogers and Hancock *(1997b)*). However, when two different thickness sheet steels are connected the thinner element is forced to carry an increased portion of the applied load via bearing resistance rather than tilting resistance. This behaviour was observed for the 042-G550/294-G250 CSIRO tests *(Macindoe and Pham, 1996)* where a pure bearing failure occurred in the thinner sheet steel. The proposed method was developed to model this type of behaviour. Statistical information calculated using the existing design standards *(SA/SNZ, 1996; CSA, 1994; AISI, 1997a; Eurocode, 1996)*, as well as the proposed method for the test specimens where two different thickness sheet steels were joined (Rogers and Hancock *(1997b)*) can be found in Table 4. Statistical information is also provided for the CSIRO test data where two different thickness sheet steels were joined *(Macindoe and Pham, 1996)* in Tables 5-7.

A distinct improvement in the mean values of the test-to-predicted ratios comparing the proposed method with the AS/NZS 4600 *(1996)* and AISI *(1997a)* Design Standards is evident for specimens where two different thickness sheet steels are connected. In the case of 042/100-G550 test specimens the mean P_{ut} / P_{up} ratio improves from 0.790 for the AS/NZS 4600 and AISI Design Standards to 1.002 for the proposed method (see Table 4). A dramatic improvement in mean test-to-predicted ratios also occurs for the 042-G550/294-G250 tests specimens where for the AS/NZS 4600 and AISI Design Standards a P_{ut} / P_{up} ratio of 0.794 was calculated and for the proposed method a ratio of 0.985 was determined (see Table 6). An improvement in mean P_{ut} / P_{up} ratios, although less significant, also occurs for the test specimens listed in Tables 5 and 7, and the 042/060-G550 and 055/080-G300 test specimens shown in Table 4.

The P_{ut} / P_{up} ratios determined using the AS/NZS 4600 *(1996)* and AISI *(1997a)* Design Standards, as well as the proposed method for all of the screwed connections test specimens included in this paper are provided in Fig. 4. This Figure shows the expected scatter of results typical for large data bases of screw connection results, mainly due to the change in connection behaviour with screw type. More importantly, these graphs show an overall improvement in mean P_{ut} / P_{up} values when the predicted ultimate connection capacities are based on the proposed method.

Table 4 042/060-G550, 042/100-G550 and 055/080-G300 Failure Based Criterion (Bearing/Tilting) Test-To-Predicted Statistical Data (Full f_u Used)

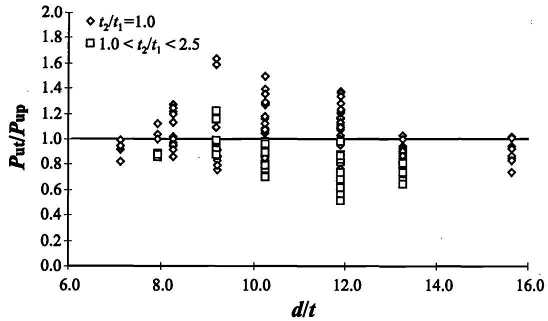
Specimen Type	*Stat. Info.*	$P_{3.0t} / P_{up}$	$P_{6.35t} / P_{up}$	P_{ut} / P_{up}	*Specimen Type*	*Stat. Info.*	$P_{3.0t} / P_{up}$	$P_{6.35t} / P_{up}$	P_{ut} / P_{up}
AS/NZS 4600 (1996) & AISI (1997a)					*Eurocode 3 (1996)*				
042/060-G550-Long	*Mean*	0.715	0.763	0.766	*042/060-G550-Long*	*Mean*	1.284	1.370	1.375
	No.	12	12	12		*No.*	12	12	12
	S.D.	0.075	0.096	0.097		*S.D.*	0.135	0.173	0.174
	C.o.V.	0.116	0.138	0.139		*C.o.V.*	0.117	0.139	0.140
042/100-G550-Long	*Mean*	0.760	0.780	0.790	*042/100-G550-Long*	*Mean*	1.009	1.035	1.049
	No.	12	12	12		*No.*	12	12	12
	S.D.	0.135	0.152	0.154		*S.D.*	0.179	0.201	0.203
	C.o.V.	0.197	0.215	0.215		*C.o.V.*	0.196	0.215	0.214
055/080-G300-Long	*Mean*	0.831	0.916	0.926	*055/080-G300-Long*	*Mean*	1.520	1.675	1.693
	No.	12	12	12		*No.*	12	12	12
	S.D.	0.082	0.123	0.143		*S.D.*	0.156	0.226	0.264
	C.o.V.	0.109	0.148	0.171		*C.o.V.*	0.113	0.149	0.172
CSA-S136 (1994)					*Proposed Method*				
042/060-G550-Long	*Mean*	1.053	1.124	1.128	*042/060-G550-Long*	*Mean*	0.773	0.824	0.827
	No.	12	12	12		*No.*	12	12	12
	S.D.	0.121	0.148	0.149		*S.D.*	0.080	0.103	0.104
	C.o.V.	0.127	0.146	0.147		*C.o.V.*	0.115	0.138	0.138
042/100-G550-Long	*Mean*	0.940	0.962	0.976	*042/100-G550-Long*	*Mean*	0.964	0.988	1.002
	No.	12	12	12		*No.*	12	12	12
	S.D.	0.149	0.158	0.168		*S.D.*	0.155	0.170	0.176
	C.o.V.	0.176	0.182	0.190		*C.o.V.*	0.178	0.190	0.194
055/080-G300-Long	*Mean*	1.148	1.264	1.278	*055/080-G300-Long*	*Mean*	0.893	0.983	0.994
	No.	12	12	12		*No.*	12	12	12
	S.D.	0.127	0.169	0.196		*S.D.*	0.085	0.129	0.152
	C.o.V.	0.122	0.148	0.169		*C.o.V.*	0.105	0.145	0.169

Table 5 CSIRO 042/060, 042/080 and 042/100-G550 Failure Based Criterion (Bearing/Tilting) Test-To-Predicted Statistical Data (Full f_u Used)

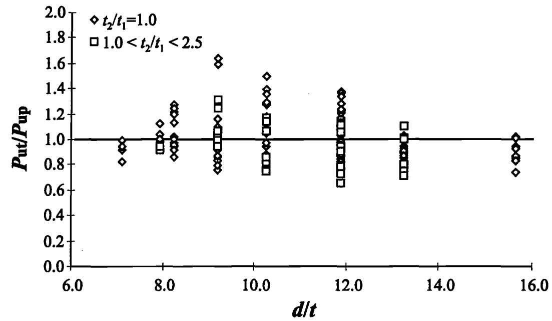
Specimen Type	*Stat. Info.*	$P_{3.0t}/P_{up}$	P_{ut}/P_{up}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997a)				*Eurocode 3 (1996)*			
042/060-G550	*Mean*	0.866	0.908	*042/060-G550*	*Mean*	1.556	1.632
	No.	3	3		*No.*	3	3
	S.D.	0.121	0.151		*S.D.*	0.217	0.271
042/080-G550	*Mean*	0.754	0.820	*042/080-G550*	*Mean*	1.264	1.376
	No.	6	6		*No.*	6	6
	S.D.	0.141	0.125		*S.D.*	0.236	0.210
	C.o.V.	0.241	0.197		*C.o.V.*	0.241	0.197
042/100-G550	*Mean*	0.823	0.851	*042/100-G550*	*Mean*	1.106	1.144
	No.	10	10		*No.*	10	10
	S.D.	0.143	0.130		*S.D.*	0.192	0.175
	C.o.V.	0.197	0.174		*C.o.V.*	0.197	0.174
CSA-S136 (1994)				*Proposed Method*			
042/060-G550	*Mean*	1.218	1.277	*042/060-G550*	*Mean*	0.920	0.965
	No.	3	3		*No.*	3	3
	S.D.	0.170	0.212		*S.D.*	0.128	0.160
042/080-G550	*Mean*	1.065	1.159	*042/080-G550*	*Mean*	0.934	1.016
	No.	6	6		*No.*	6	6
	S.D.	0.199	0.177		*S.D.*	0.174	0.155
	C.o.V.	0.241	0.197		*C.o.V.*	0.241	0.197
042/100-G550	*Mean*	0.983	1.016	*042/100-G550*	*Mean*	1.020	1.055
	No.	10	10		*No.*	10	10
	S.D.	0.171	0.156		*S.D.*	0.177	0.162
	C.o.V.	0.197	0.174		*C.o.V.*	0.197	0.174

Table 6 CSIRO 042-G550/294-G250, 075-G550/294-G250 and 100-G550/294-G250 Failure Based Criterion (Bearing/Tilting) Test-To-Predicted Statistical Data (Full f_u Used)

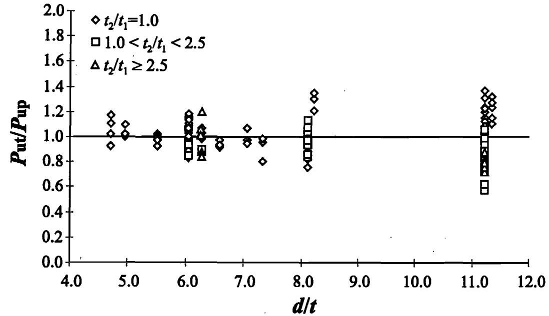
Specimen Type	*Stat. Info.*	$P_{3.0t}/P_{up}$	P_{ut}/P_{up}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997a)				*Eurocode 3 (1996)*			
042-G550/ 294-G250	*Mean*	0.770	0.794	*042-G550/ 294-G250*	*Mean*	0.991	1.021
	No.	6	6		*No.*	6	6
	S.D.	0.082	0.056		*S.D.*	0.106	0.072
	C.o.V.	0.138	0.091		*C.o.V.*	0.138	0.091
075-G550/ 294-G250	*Mean*	0.863	0.970	*075-G550/ 294-G250*	*Mean*	1.109	1.248
	No.	3	3		*No.*	3	3
	S.D.	0.158	0.195		*S.D.*	0.204	0.251
100-G550 294-G250	*Mean*	0.865	1.027	*100-G550 294-G250*	*Mean*	1.112	1.320
	No.	3	3		*No.*	3	3
	S.D.	0.109	0.027		*S.D.*	0.140	0.034
CSA-S136 (1994)				*Proposed Method*			
042-G550/ 294-G250	*Mean*	0.778	0.802	*042-G550/ 294-G250*	*Mean*	0.955	0.985
	No.	6	6		*No.*	6	6
	S.D.	0.083	0.057		*S.D.*	0.102	0.070
	C.o.V.	0.138	0.091		*C.o.V.*	0.138	0.091
075-G550/ 294-G250	*Mean*	0.776	0.873	*075-G550/ 294-G250*	*Mean*	0.872	0.980
	No.	3	3		*No.*	3	3
	S.D.	0.143	0.176		*S.D.*	0.160	0.197
100-G550 294-G250	*Mean*	0.778	0.924	*100-G550 294-G250*	*Mean*	0.873	1.037
	No.	3	3		*No.*	3	3
	S.D.	0.098	0.024		*S.D.*	0.110	0.027



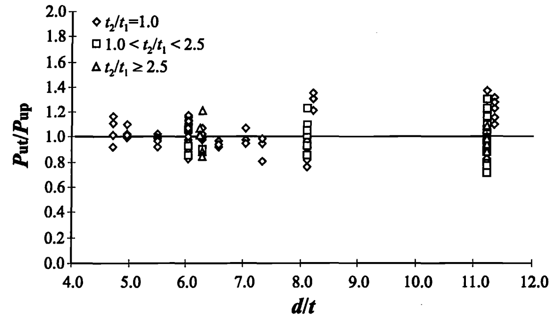
Rogers and Hancock AS/NZS 4600 & AISI P_{ut}/P_{up} vs. d/t



Rogers and Hancock Proposed Method P_{ut}/P_{up} vs. d/t



CSIRO AS/NZS 4600 & AISI P_{ut}/P_{up} vs. d/t



CSIRO Proposed Method P_{ut}/P_{up} vs. d/t

Fig. 4 Rogers and Hancock *(1997c)* as well as CSIRO *(Macindoe and Pham, 1996)* AS/NZS 4600 & AISI P_{ut}/P_{up} vs. d/t Graphs

Table 7 CSIRO 060/080, 060/100, 075/095 and 080/100-G550 Failure Based Criterion (Bearing/Tilting) Test-To-Predicted Statistical Data (Full f_u Used)

Specimen Type	*Stat. Info.*	$P_{3.0t}/P_{up}$	P_{ut}/P_{up}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997a)				*Eurocode 3 (1996)*			
060/080-G550	*Mean*	0.893	0.986	*060/080-G550*	*Mean*	1.488	1.642
	No.	3	3		*No.*	3	3
	S.D.	0.173	0.128		*S.D.*	0.288	0.214
060/100-G550	*Mean*	0.836	0.973	*060/100-G550*	*Mean*	1.415	1.647
	No.	4	4		*No.*	4	4
	S.D.	0.052	0.115		*S.D.*	0.088	0.195
	C.o.V.	0.107	0.205		*C.o.V.*	0.107	0.205
075/095-G550	*Mean*	0.887	0.895	*075/095-G550*	*Mean*	1.627	1.640
	No.	5	5		*No.*	5	5
	S.D.	0.011	0.006		*S.D.*	0.020	0.012
	C.o.V.	0.018	0.010		*C.o.V.*	0.018	0.010
080/100-G550	*Mean*	0.845	0.876	*080/100-G550*	*Mean*	1.406	1.459
	No.	3	3		*No.*	3	3
	S.D.	0.049	0.046		*S.D.*	0.082	0.077
CSA-S136 (1994)				*Proposed Method*			
060/080-G550	*Mean*	1.140	1.259	*060/080-G550*	*Mean*	0.913	1.008
	No.	3	3		*No.*	3	3
	S.D.	0.221	0.164		*S.D.*	0.177	0.131
060/100-G550	*Mean*	1.105	1.285	*060/100-G550*	*Mean*	0.907	1.056
	No.	4	4		*No.*	4	4
	S.D.	0.068	0.152		*S.D.*	0.056	0.125
	C.o.V.	0.107	0.205		*C.o.V.*	0.107	0.205
075/095-G550	*Mean*	1.362	1.373	*075/095-G550*	*Mean*	0.889	0.897
	No.	5	5		*No.*	5	5
	S.D.	0.017	0.010		*S.D.*	0.011	0.006
	C.o.V.	0.018	0.010		*C.o.V.*	0.018	0.010
080/100-G550	*Mean*	1.193	1.238	*080/100-G550*	*Mean*	0.845	0.877
	No.	3	3		*No.*	3	3
	S.D.	0.070	0.065		*S.D.*	0.050	0.046

4.3 Limit States Calibration of the Proposed Method

The proposed method for bearing and bearing/tilting resistance was calibrated according to the procedure specified in the AISI Commentary *(AISI, 1997b).* All of the screwed connection test data included in this paper was used to provide the necessary statistical information. The statistical data contained in Table 8 is the mean of the 042-G550 longitudinal, transverse and diagonal results shown in Rogers and Hancock *(1996).* Although the information on sheet steel variability used in this paper is based on an investigation of 042-G550 test specimens *(BHP, 1996)* (see Rogers and Hancock *(1996)*), it was assumed that all of the sheet steel types could be defined by the same mean values and coefficients of variation for material properties and fabrication variables.

The target reliability indices, β_o, were defined as 3.5, 4.0 and 4.5, however, only the results for $\beta_o = 3.5$ are discussed in this paper (see Rogers and Hancock *(1997b)* for results using $\beta_o = 4.0$ and 4.5). The calibration information from the screwed connection tests completed for this paper and by the CSIRO *(Macindoe and Pham, 1996)*, which includes the specimens composed of variable as well as equal thickness sheet steels, is shown in Table 9. Calibration of the proposed method for bearing and bearing/tiling failure was completed using both the full value of the ultimate strength, f_u, and the reduced value specified for thin G550 sheet steels, $0.75f_u$. Calibration of the proposed method using the reduced ultimate strength is not entirely correct because a proportion of the test specimens used as data meet the ductility requirements specified in the current design standards *(SA/SNZ, 1996; CSA, 1994; AISI, 1997a).*

Table 8 AISI Derived Resistance (Capacity) Factor, ϕ, Statistical Data for the Proposed Method

Stat. Info.	*Mean Value*	*Stat. Info.*	*Mean Value*
$\bar{f}_{u,Comm}$ (MPa)	758	$\bar{t}_{b,Comm}$ (mm)	0.41
$\bar{f}_{u,SU}$ (MPa)	684	$\bar{t}_{b,SU}$ (mm)	0.41
$\bar{f}_{u,BHP}$ (MPa)	703	$\bar{t}_{b,BHP}$ (mm)	0.42
M_m	1.342	F_m	0.968
M_m *(with* $0.75f_u$*)*	1.789	V_F	0.0161
V_M	0.0545		

Table 9 AISI Derived Resistance (Capacity) Factors, ϕ, for Bearing/Tilting Connection Failure Using the Proposed Method

Data Type	*Stat. Info.*	*Rogers & Hancock*	*Macindoe & Pham*
Test Data P_{ut} / P_{up}	*Mean*	1.004	1.013
	No.	150	158
	S.D.	0.191	0.126
	C.o.V.	0.192	0.125
Calibration Data P_{ut} / P_{up}	P_m *(with full* f_u*)*	1.004	1.013
	P_m *(with* $0.75f_u$*)*	1.338	1.351
	V_P	0.192	0.125
	β_o	3.5	3.5

Load Comparison	*Stat. Info.*	*Rogers & Hancock*	*Macindoe & Pham*
P_{ut} / P_{up}	ϕ *(calc. full* f_u*)*	0.68	0.79
Australia (SA/SNZ, 1996)	ϕ *(calc. 0.75* f_u*)*	1.21	1.41
	ϕ *(current)*	0.50	0.50
P_{ut} / P_{up}	ϕ *(calc. full* f_u*)*	0.72	0.83
New Zealand (SA/SNZ, 1996)	ϕ *(calc. 0.75* f_u*)*	1.28	1.48
& USA (AISI, 1997a)	ϕ *(current)*	0.50	0.50
P_{ut} / P_{up}	ϕ *(calc. full* f_u*)*	0.68	0.79
Canada (CSA, 1994)	ϕ *(calc. 0.75* f_u*)*	1.21	1.41
	ϕ *(current)*	0.75	0.75
P_{ut} / P_{up}	ϕ *(calc. full* f_u*)*	0.69	0.80
Europe (Eurocode, 1996)	ϕ *(calc. 0.75* f_u*)*	1.23	1.42
	$1/\gamma_{M2}$ *(current)*	0.80	0.80

Resistance factors determined using the Australian *(SA, 1989)*, New Zealand *(SNZ, 1992)* and USA *(AISI, 1997a)* dead and live load factors with the P_{ut} / P_{up} ratios for all of the data considered exceed the required $\phi = 0.50$. However, calculated resistance factors for the Canadian *(CSA, 1994)* and European *(Eurocode, 1996)* dead and live load factors only exceed the required $\phi = 0.75$ and $\phi = 0.80$, respectively, for $\beta_o = 3.5$ with the CSIRO data *(Macindoe and Pham, 1996)*. If the $0.75f_u$ reduction factor is applied to all of the test data, the calculated capacity factors increase to values far above the required capacity factors currently used in the bearing and bearing/tilting design of screwed connections.

5 CONCLUSIONS

The results of screwed connection tests completed for this paper and by the CSIRO *(Macindoe and Pham, 1996)* indicate that The AS/NZS 4600 *(1996)*, CSA-S136 *(1994)* and AISI *(1997a)* Design Standards provide accurate load predictions when the two connected sheet steels are of similar thickness. Failure is more likely to depend on tilting of the screws and the corresponding tilting formulations control in design when a screwed connection is composed of two similar thickness sheet steels. However, when two different thickness sheet steels are connected with screws failure will more likely result from bearing distress in the thinner of the connected elements. Proper analysis of this phenomena requires an accurate bearing formulation. The accuracy of the AS/NZS 4600, CSA-S136 and AISI Design Standards when used to estimate the bearing resistance of screwed connections diminishes as the relative difference in thickness between the two connected elements increases, and the connection is forced to fail in a bearing mode rather than a combined bearing/tilting mode. Hence, it is necessary that the coefficient used in the bearing formulations for screwed connections be reduced to limit the existing unconservative nature of these design standards.

The proposed method of analysis for screwed connections loaded in shear can be used to improve the accuracy of predicted load resistance when two different thickness sheet steels are joined. It is recommended that the variable bearing coefficient formulation be used in the design of screwed connections.

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