Behaviour of Thin G550 Sheet Steel Screwed Connections

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SUMMARY

This paper provides a summary of results detailing the behaviour of screwed connections tested in shear, which were composed of thin G550 and G300 sheet steels (to the 1993 Australian Standard AS 1397). Recommendations concerning the adequacy of current design standards with respect to the design of thin sheet steel screwed connections are made.

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, 1997)* 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, 1997)* 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.

This paper reports on the testing of single overlap screwed connections concentrically loaded in shear, and fabricated with multiple point fasteners using G550 and G300 sheet steels (see AS 1397 *(1993)*). Sheet steels which range in base metal thickness from 0.42-1.00 mm were tested, where the type, number and placement of screws were varied to observe the behaviour of connections which undergo combined bearing/tilting failure *(Rogers and Hancock, 1997c)*. 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.

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2 Cold Formed Steel Screwed Connection Design Provisions

An overview of the design equations used for the prediction of connection capacity is provided in this section. The nominal cross-section tension resistance of a member which is not subject to shear lag and fails by material yielding of the gross cross-section is formulated for all of the design standards, except for the AISI Specification *(1997)*, as follows,

$$N_t = A_g f_y \tag{1}$$

where A_g is the gross cross-sectional area and f_y is the 0.2% proof stress or yield stress. The nominal cross-section tension capacity of a member which is not subject to shear lag and fails by rupture of the net cross-section away from connections is represented for all of the design standards, except for the AISI Specification *(1997)*, by the following equation,

$$N_t = A_n f_u \tag{2}$$

where A_n is the net cross-sectional area and f_u is the ultimate strength. (Note: the formulae contained in (1) and (2) are under review for inclusion in the AISI Specification *(1997)* in AISI Ballot C/S96-66B *(1996)*).

The Australia / New Zealand *(SA/SNZ, 1996)* and USA *(AISI, 1997)* Design Standards have separate requirements for the net cross-section tension capacity at connections. The design equation for the AS/NZS 4600 and AISI Design Standards is as follows,

$$N_f = \left(1.0 - r + \frac{2.5rd}{s}\right) A_n f_u \le A_n f_u \tag{3}$$

where r is the ratio of the force transmitted by the screw(s) divided by the tensile force in the member at that section, d is the diameter of the screw(s), and s is the spacing of the screws perpendicular to the line of the force, or for a single screw the width of the sheet. The CSA-S136 *(1994)* and Eurocode 3 *(1996)* Design Standards do not contain a stress reduction factor based on the number and position of screws in the cross-section, as formulated in (3). Net cross-section tension capacity at a connection is determined as found in (2).

The design bearing capacity per screw for connections regardless of the design standard used is as follows,

$$V_b = C f_u d t \tag{4}$$

where C is a variable bearing coefficient. The Australian / New Zealand *(SA/SNZ, 1996)* and USA *(AISI, 1997)* 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
$d/t \le 10$	3
$10 < d/t < 15$	$30\, t/d$
$d/t \ge 15$	2

thickness, as listed in Table 1. The Australian / New Zealand and USA Design Standards specify that for a single shear connection where $t_2 / t_1 \le 1.0$ and the two sheets are in contact at the screw position, the nominal bearing capacity is taken as the smaller of (5)-(7).

$$V_b = 4.2\sqrt{(t_2^3 d)}\, f_{u2} \tag{5}$$

$$V_b = 2.7 t_1 d f_{u1} \tag{6}$$
$$V_b = 2.7 t_2 d f_{u2} \tag{7}$$

where (5) 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:

$$V_b = 2.7 t_1 d f_{u1} \tag{8}$$
$$V_b = 2.7 t_2 d f_{u2} \tag{9}$$

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 (5)-(7) and the minimum value obtained from (8) and (9). Only the Australian / New Zealand *(SA/SNZ, 1996)* and USA *(AISI, 1997)* 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.

$$B_r = C\,(t_1 + t_2)\, d\, f_{u1} / 4 \tag{10}$$

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, 1997)* 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 (5)).

$$F_{b,Rd} = \alpha f_u\, d\, t_1 \tag{11}$$

where α is defined as follows;

if $t_1 = t_2$ $\quad \alpha = 3.2\sqrt{t_1/d} \leq 2.1$ (12)

if $t_2 \geq 2.5\, t_1$ $\quad \alpha = 2.1$ (13)

If $t_1 < t_2 \leq 2.5\, t_1$ then α is obtained by linear interpolation between (12) and (13).

3 Screwed Connection Tests and Results

3.1 General

One hundred and fifty single overlap screwed connection specimens with multiple point fasteners were tested in shear at the University of Sydney. The main objectives of this experimental testing phase were to observe the behaviour and to evaluate the existing design provisions for screwed connections fabricated from thin G550 sheet steels. Five different sheet steels were used in the tests, including both G550 and G300 grades. The results have been used as a basis for comparison with the current design equations specified in the Australian / New Zealand *(SA/SNZ, 1996)*, North American *(CSA, 1994; AISI, 1997)* and European *(Eurocode, 1996)* Cold Formed Steel Design Standards. All steels were cold reduced to thickness and annealed dependent on the G550 or G300 classification, had an aluminum/zinc alloy (zincalume-AZ) coating and were obtained from standard coils during normal rolling operations. The material properties of cold reduced steels have been shown to be anisotropic *(Rogers and Hancock, 1996, 1997a)*, hence, specimens were cut from three directions within the sheet; longitudinal, transverse and diagonal, with respect to the rolling direction. The combinations of sheet steels used for the screwed connection tests completed for this paper are as follows:

- 042/042-G550
- 042/060-G550
- 042/100-G550
- 060/060-G550
- 055/055-G300
- 055/080-G300

where, e.g., 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. Note: when a connection specimen was composed of two different thickness sheet steels, the thinner sheet steel was placed adjacent to the screw head.

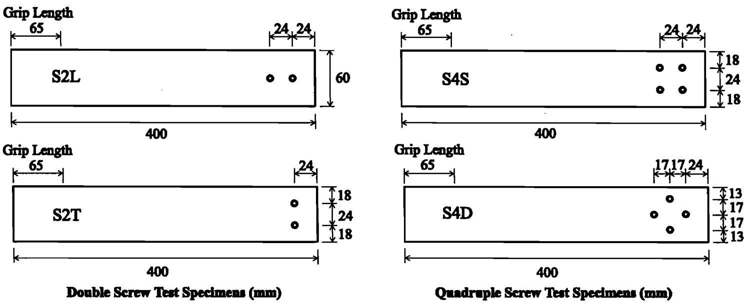

Fig. 1 Screwed Connection Specimens - Nominal Dimensions

Connections were tested in shear with various type, number and arrangement of screws (see Fig. 1). The possibility of screw shear failure was eliminated by using appropriate size and strength HITEKS and STITCH screws (see Fig. 2). The eight types of screws used for the connection tests are as follows.

- 8-15×15 mm STITCH Hexagon Slot Head Needle Point (4.20 mm nom. dia.)
- 8-18×12 mm HITEKS Hexagon Head (4.20 mm nom. dia.)
- 10-16×20 mm HITEKS Special Pan Head (4.87 mm nom. dia.)
- 10-12×20 mm STITCH Hexagon Head Needle Point (4.87 mm nom. dia.)
- 10-16×16 mm HITEKS Hexagon Head (4.87 mm nom. dia.)
- 12-14×20 mm HITEKS Hexagon Head (5.43 mm nom. dia.)
- 12-24×20 mm HITEKS Hexagon Head (5.43 mm nom. dia.)
- 14-10×20 mm HITEKS Hexagon Head (6.41 mm nom. dia.)

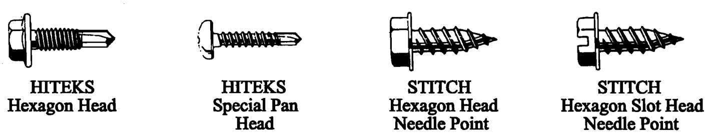

Fig. 2 Screw Fastener Types

A gripping apparatus was fabricated so that each end of the test specimen was joined by a pin assembly to the test machine grip. The gripping apparatus was designed to eliminate slippage of the gripped section of the test specimens and to transfer load evenly to the entire cross-section (see Fig. 3). The gripped end of each test specimen was kept constant at 65 mm, and shims were not required because the thickness of the sheet steels was less than 2 mm *(ECCS, 1983)*.

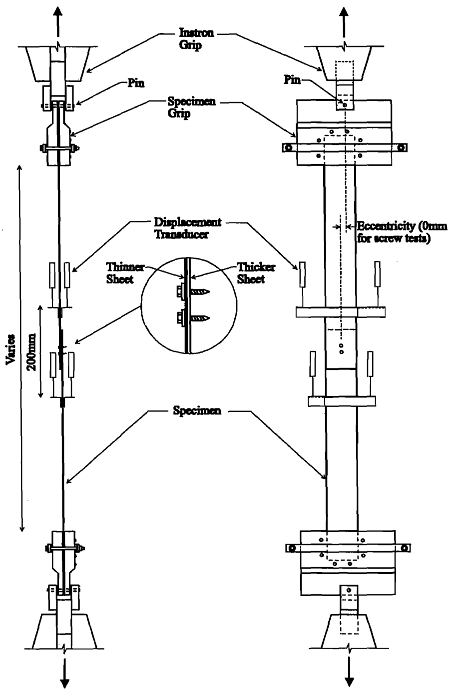

Fig. 3 Schematic Drawing of Screwed Connection Test Set-Up

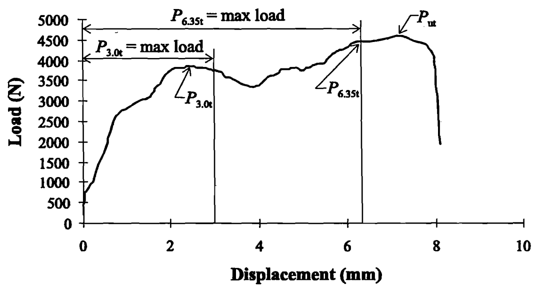

Fig. 4 Definition of P_{ut}, $P_{3.0t}$ and $P_{6.35t}$

The ultimate load, P_{ut}, and displacement at ultimate, δ_{ult}, were obtained for each of the screw connection test specimens, along with the 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 Fig. 4). The connection displacement, necessary to determine the serviceability based loads, was measured from the point of initial loading of each test, due to the lack of connection slip with the use of self drilling, self tapping screws.

3.2 Basic Material Properties

All G550 sheet steels tested for this project yielded gradually with minimal strain hardening, whereas the G300 sheet steels displayed a sharp yield point, followed by a yield plateau then a strain hardening region. Yield stress values for the G550 sheet steels were calculated using the 0.2% proof stress method. The lack of a strain hardening range for the G550 materials is indicated by the consistent ultimate strength to yield stress ratios, f_u / f_y, of unity. Only the longitudinal 100-G550 tensile specimens had an f_u value which exceeded f_y, where $f_u / f_y = 1.04$. The G550 sheet steels do not meet the Dhalla and Winter *(1974b)* or current design standard *(SA/SNZ, 1996; CSA, 1994; AISI, 1997)* material requirements which allow for the full yield stress and ultimate strength to be used in design, i.e. the ultimate strength to yield stress ratio, $f_u / f_y \geq 1.08$.

Table 2 Material Properties of Sheet Steels (Mean Values)

Specimen Type	*Direction*	t_b (mm)	f_y^a (MPa)	f_u^a (MPa)	f_u / f_y^a
042-G550	*Longitudinal*	0.41	718/701	718/701	1.00/1.00
	Transverse	0.41	821/805	821/805	1.00/1.00
	Diagonal	0.41	728/713	728/713	1.00/1.00
060-G550	*Longitudinal*	0.59	719/705	719/705	1.00/1.00
	Transverse	0.59	801/788	801/788	1.00/1.00
	Diagonal	0.59	725/712	725/712	1.00/1.00
100-G550	*Longitudinal*	0.99	610/594	636/620	1.04/1.04
	Transverse	0.99	698/678	698/678	1.00/1.00
	Diagonal	0.99	652/636	652/636	1.00/1.00
055-G300	*Longitudinal*	0.53	369/342	417/390	1.13/1.14
	Transverse	0.53	387/361	418/392	1.08/1.09
	Diagonal	0.53	389/362	423/397	1.09/1.09
080-G300	*Longitudinal*	0.79	358/338	410/390	1.15/1.15
	Transverse	0.79	378/359	413/393	1.09/1.10
	Diagonal	0.79	375/355	422/403	1.13/1.13

Note: Material properties were calculated using the base metal thickness.
[a] *Dynamic/Static* values given.

The material properties for the 0.42 mm and 0.60 mm G550 sheet steels are dependent on the direction from which the coupons were obtained. Yield stress and ultimate strength values are significantly higher for specimens milled from the transverse direction in comparison to specimens cut from the longitudinal and diagonal directions. A less extreme variation in material properties occurs for the thicker 1.00 mm G550 sheet steel. The material properties of the G300 sheet steels are not dependent on direction within the plane of the sheet (see Table 2).

3.3 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. All connections tested were designed such that screw shear did not occur, hence, only failure of the sheet steel was considered. Specimens were dimensioned and screws were positioned, such that only bearing, tilting and combined bearing/tilting failures were possible (see Fig. 5). 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. It is also possible for tilting failure of the screw connection to occur due to the eccentric shear load placed

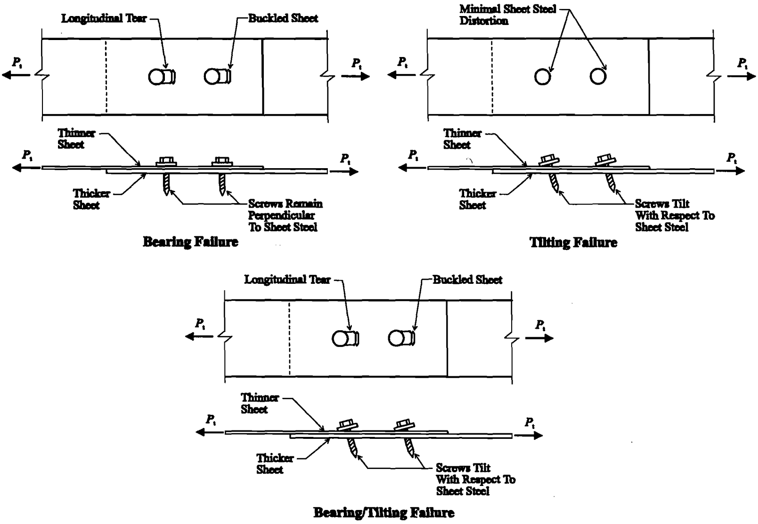

Fig. 5 Screwed Connection Failure Patterns

on the screw by the two joined sheets. For certain materials failure by pure tilting may result, where the sheet steel adjacent to the screw fastener is minimally distorted, and ultimate failure is due to a pull-out action of the screw after significant tilting. Pull-out failure is caused by a build-up of axial tensile forces in the screw, which result from the rotated position of the fastener with respect to the direction of load in the connection. However, the pure bearing or tilting failure modes were not observed in any of the tests completed for this report. The mode of failure recorded for all screw connection tests 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.

3.4 Comparison of Ultimate Test-to-Design Standard Predicted Loads

Dynamic ultimate test loads, P_{ut}, were used in comparison with predicted ultimate connection strengths, P_{up}, determined using the relevant design standards *(SA/SNZ, 1996; CSA, 1994; AISI, 1997; Eurocode, 1996)* with the full material properties. Conclusions regarding the adequacy of design formulations based on a comparison of test-to-predicted ratios where the actual and predicted failure modes do not match are invalid. Hence, statistical information of the test-to-predicted ratios for the various design standards is not provided in this paper. Only the CSA-S136 *(1994)* and Eurocode *(1996)* Design Standards adequately predict the failure mode of the different G550 test specimens.

The ratio of correct-to-incorrect failure mode prediction for the AS/NZS *(1996)* and AISI *(1997)* Design Standards is 134:16, where the incorrect predictions were defined as net section failure when bearing/tilting failure occurred in the test specimen. The error in predicted failure mode can be attributed to design equations which underestimate the net section fracture resistance.

The failure modes for the 042/042-G550, 060/060-G550 and 055/055-G300 test specimens could be accurately predicted using the AS/NZS and AISI Design Standards when the $0.75f_u$ factor was not applied for the G550 sheet steels. However, failure modes for the 042/060-G550, 042/100-G550 and 055/080-G300 test specimens could not be accurately predicted. The stress reduction factor used in the calculation of net cross-section fracture loads is unnecessary for screwed connections.

3.5 Comparison of Ultimate Test-to-Failure Criterion Predicted Loads

The predicted ultimate connection capacity, P_{up}, used in comparison with the ultimate, P_{ut}, and serviceability loads, $P_{3.0t}$ and $P_{6.35t}$, of each screwed connection were calculated using the design equation developed for the bearing/tilting failure mode with the full material properties. This type of failure based criterion comparison reveals the accuracy of the individual design formulation by eliminating the influence of the remaining screwed connection design provisions. Statistical results for each material type and design standard are provided for 042/042-G550, 060/060-G550, 042/060-G550 & 042/100-G550 and 055/055-G300 & 055/080-G300 sheet steel connections in Tables 3, 4, 5 and 6, respectively.

The ultimate and serviceability bearing/tilting connection resistance of the screw test specimens determined using the Eurocode 3 Design Standard *(1996)* provides the most conservative estimate of the load carrying capacity. The test-to-predicted ratios exceed 1.0 for all load combinations, directions and sheet steel types. For 042/042-G550 screw connections P_{ut} / P_{up}, $P_{3.0t} / P_{up}$, and $P_{6.35t} / P_{up}$ mean values range from 1.215 to 1.397 (see Table 3). Test data from connections composed of the other sheet steel types indicates that for 042/100-G550 screw specimens the test-to-predicted values exceed unity yet are less conservative. However, for all connections fabricated using G300 sheet steels the Eurocode 3 Design Standard is more conservative when used to predict the capacity of a single overlap screwed connection, i.e. P_{ut} / P_{up}, $P_{3.0t} / P_{up}$, and $P_{6.35t} / P_{up}$ ratios are as high as 1.693.

This conservative trend in test-to-predicted ratios is not evident for all types of test specimens when using the AS/NZS 4600 *(1996)* and AISI *(1997)* Design Standards. These design standards can be used to conservatively estimate the load carrying capacity of longitudinal and diagonal 042/042 G550 connections, longitudinal 060/060-G550 connections excluding $P_{3.0t} / P_{up}$, and 055/055-G300 connections. In all other cases the test-to-predicted ratios were found to be less than unity. Screw connections composed of 042/060-G550 and 042/100-G550 sheet steels have the most unconservative test-to-predicted ratios with $P_{3.0t} / P_{up}$ values as low as 0.715. For the design case where two different thickness sheet steels are connected with screws, and the thinner sheet steel is placed adjacent to the screw head, the capacity of the connection becomes increasingly dependent on the bearing provisions as the relative difference in thickness increases. Since a large drop in the ability to accurately predict the failure loads of 042/060-G550 and 042/100-G550 connections occurs with the AS/NZS 4600 and AISI Design Standards, it appears that the bearing formulation specified for screwed connections is unconservative. This is similar to the behaviour observed for bolted connection tests of thin G550 and G300 sheet steels *(Rogers and Hancock, 1997b)*.

The CSA-S136 Design Standard *(1994)* provides conservative predictions of the bearing/tilting capacity of screwed connections for the longitudinal 042/042-G550, longitudinal 042/060-G550 and all G300 sheet steels tested. Test specimens fabricated using transverse and diagonal 042/042-G550, 060/060-G550 and 042/100-G550 sheet steels all provide mean test-to-predicted ratios which are below 1.0. The majority of these P_{ut} / P_{up}, $P_{3.0t} / P_{up}$, and $P_{6.35t} / P_{up}$ ratios range between 0.90 and 1.0, although some of the serviceability $P_{3.0t} / P_{up}$ ratios are slightly below 0.90.

Table 3 042/042-G550 Failure Based Criterion (Bearing/Tilting) Test-To-Predicted Statistical Data (Full f_u Used)

Specimen Type	*Stat. Info.*	$P_{3.0t}/P_{up}$	$P_{6.35t}/P_{up}$	P_{ut}/P_{up}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	$P_{6.35t}/P_{up}$	P_{ut}/P_{up}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	$P_{6.35t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997)					*CSA-S136 (1994)*					*Eurocode 3 (1996)*				
Longitudinal	*Mean*	1.047	1.061	1.065	*Longitudinal*	*Mean*	1.015	1.028	1.032	*Longitudinal*	*Mean*	1.374	1.392	1.397
	No.	32	32	32		*No.*	32	32	32		*No.*	32	32	32
	S.D.	0.204	0.207	0.204		*S.D.*	0.181	0.183	0.181		*S.D.*	0.268	0.272	0.268
	C.o.V.	0.202	0.202	0.198		*C.o.V.*	0.184	0.184	0.181		*C.o.V.*	0.202	0.202	0.198
Transverse	*Mean*	0.925	0.940	0.943	*Transverse*	*Mean*	0.899	0.913	0.915	*Transverse*	*Mean*	1.215	1.234	1.237
	No.	32	32	32		*No.*	32	32	32		*No.*	32	32	32
	S.D.	0.141	0.143	0.142		*S.D.*	0.129	0.130	0.127		*S.D.*	0.186	0.188	0.186
	C.o.V.	0.158	0.158	0.156		*C.o.V.*	0.148	0.147	0.144		*C.o.V.*	0.158	0.158	0.156
Diagonal	*Mean*	1.038	1.046	1.046	*Diagonal*	*Mean*	0.966	0.973	0.973	*Diagonal*	*Mean*	1.362	1.372	1.372
	No.	14	14	14		*No.*	14	14	14		*No.*	14	14	14
	S.D.	0.205	0.196	0.196		*S.D.*	0.191	0.182	0.182		*S.D.*	0.269	0.258	0.258
	C.o.V.	0.215	0.204	0.204		*C.o.V.*	0.215	0.204	0.204		*C.o.V.*	0.215	0.204	0.204

Table 4 060/060-G550 Failure Based Criterion (Bearing/Tilting) Test-To-Predicted Statistical Data (Full f_u Used)

Specimen Type	*Stat. Info.*	$P_{3.0t}/P_{up}$	$P_{6.35t}/P_{up}$	P_{ut}/P_{up}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	$P_{6.35t}/P_{up}$	P_{ut}/P_{up}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	$P_{6.35t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997)					*CSA-S136 (1994)*					*Eurocode 3 (1996)*				
Longitudinal	*Mean*	0.934	1.006	1.006	*Longitudinal*	*Mean*	0.916	0.987	0.987	*Longitudinal*	*Mean*	1.226	1.320	1.320
	No.	8	8	8		*No.*	8	8	8		*No.*	8	8	8
	S.D.	0.072	0.116	0.116		*S.D.*	0.075	0.127	0.127		*S.D.*	0.095	0.152	0.152
	C.o.V.	0.091	0.136	0.136		*C.o.V.*	0.097	0.153	0.153		*C.o.V.*	0.091	0.136	0.136
Transverse	*Mean*	0.860	0.925	0.925	*Transverse*	*Mean*	0.844	0.908	0.908	*Transverse*	*Mean*	1.129	1.214	1.214
	No.	8	8	8		*No.*	8	8	8		*No.*	8	8	8
	S.D.	0.090	0.160	0.160		*S.D.*	0.098	0.164	0.164		*S.D.*	0.119	0.210	0.210
	C.o.V.	0.124	0.204	0.204		*C.o.V.*	0.137	0.214	0.214		*C.o.V.*	0.124	0.204	0.204
Diagonal	*Mean*	0.912	0.987	0.987	*Diagonal*	*Mean*	0.896	0.970	0.970	*Diagonal*	*Mean*	1.198	1.296	1.296
	No.	8	8	8		*No.*	8	8	8		*No.*	8	8	8
	S.D.	0.093	0.154	0.154		*S.D.*	0.113	0.165	0.165		*S.D.*	0.122	0.202	0.202
	C.o.V.	0.120	0.184	0.184		*C.o.V.*	0.150	0.202	0.202		*C.o.V.*	0.120	0.184	0.184

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

Specimen Type	*Stat. Info.*	$P_{3.0t}/P_{up}$	$P_{6.35t}/P_{up}$	P_{ut}/P_{up}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	$P_{6.35t}/P_{up}$	P_{ut}/P_{up}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	$P_{6.35t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997)					*CSA-S136 (1994)*					*Eurocode 3 (1996)*				
042/060-G550-Long	*Mean*	0.715	0.763	0.766	*042/060-G550-Long*	*Mean*	1.053	1.124	1.128	*042/060-G550-Long*	*Mean*	1.284	1.370	1.375
	No.	12	12	12		*No.*	12	12	12		*No.*	12	12	12
	S.D.	0.075	0.096	0.097		*S.D.*	0.121	0.148	0.149		*S.D.*	0.135	0.173	0.174
	C.o.V.	0.116	0.138	0.139		*C.o.V.*	0.127	0.146	0.147		*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*	0.940	0.962	0.976	*042/100-G550-Long*	*Mean*	1.009	1.035	1.049
	No.	12	12	12		*No.*	12	12	12		*No.*	12	12	12
	S.D.	0.135	0.152	0.154		*S.D.*	0.149	0.158	0.168		*S.D.*	0.179	0.201	0.203
	C.o.V.	0.197	0.215	0.215		*C.o.V.*	0.176	0.182	0.190		*C.o.V.*	0.196	0.215	0.214

Table 6 055/055-G300 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}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	$P_{6.35t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997)					*CSA-S136 (1994)*					*Eurocode 3 (1996)*				
055/055-G300-Long	*Mean*	1.153	1.204	1.205	*055/055-G300-Long*	*Mean*	1.076	1.123	1.124	*055/055-G300-Long*	*Mean*	1.513	1.580	1.581
	No.	12	12	12		*No.*	12	12	12		*No.*	12	12	12
	S.D.	0.177	0.254	0.254		*S.D.*	0.160	0.231	0.231		*S.D.*	0.232	0.333	0.334
	C.o.V.	0.169	0.233	0.233		*C.o.V.*	0.165	0.227	0.227		*C.o.V.*	0.169	0.233	0.233
055/080-G300-Long	*Mean*	0.831	0.916	0.926	*055/080-G300-Long*	*Mean*	1.148	1.264	1.278	*055/080-G300-Long*	*Mean*	1.520	1.675	1.693
	No.	12	12	12		*No.*	12	12	12		*No.*	12	12	12
	S.D.	0.082	0.123	0.143		*S.D.*	0.127	0.169	0.196		*S.D.*	0.156	0.226	0.264
	C.o.V.	0.109	0.148	0.171		*C.o.V.*	0.122	0.148	0.169		*C.o.V.*	0.113	0.149	0.172

4 CSIRO SCREW CONNECTION TEST RESULTS

4.1 General

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).* The aim of this CSIRO project was to provide information which could be used to evaluate the performance of screwed and blind riveted connections found in the Australian steel house framing industry. 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. The combinations of sheet steels used for the CSIRO screwed connections included in this paper are as follows.

- 042/042-G550
- 060/060-G550
- 075/075-G550
- 080/080-G550
- 095/095-G550
- 100/100-G550
- 042/060-G550
- 042/080-G550
- 042/100-G550
- 060/060-G550
- 060/100-G550
- 075/095-G550
- 080/100-G550
- 042-G550/294-G250
- 075-G550/294-G250
- 100-G550/294-G250

The additional CSIRO data consists of 134 single screw tests (S1L), 12 double screw longitudinal tests (S2L) and 12 double screw transverse tests (S2T) (see Fig. 1). Four different types of self drilling / self tapping screws (see Fig. 2) were used to connect the various sheet steels.

- 10-16×16 mm HITEKS Hexagon Head (4.87 mm nom. dia.)
- 10-12×20 mm STITCH Hexagon Head Needle Point (4.87 mm nom. dia.)
- 12-14×20 mm HITEKS Hexagon Head (5.43 mm nom. dia.)
- 14-10×20 mm HITEKS Hexagon Head (6.41 mm nom. dia.)

4.2 CSIRO Test Results

The authors of the current paper have completed an in-depth series of tests on screwed connections composed of thin G550 sheet steels. All of the tests exhibited an ultimate failure resulting from a combination of bearing and tilting of the screw fasteners. It was not possible to isolate either bearing or tilting failure as the primary cause of the loss of load carrying ability in any of the tested connections. For this reason all of the test specimens composed entirely of G550 sheet steels completed by the CSIRO *(Macindoe and Pham, 1996)* which failed by either bearing or tilting were grouped into a combined bearing/tilting failure category. However, there are 12 test specimens in which a 2.94 mm G250 sheet steel was used in the connection to force a bearing failure in the attached thinner G550 sheet steel. These specimens were analysed using the bearing formulations contained in the respective design standards.

Statistical information which details the bearing/tilting failure criterion test-to-predicted loads for the Australian / New Zealand *(SA/SNZ, 1996)*, North American *(CSA, 1994; AISI, 1997)* and European *(Eurocode, 1996)* Design Standards can be found in Tables 7-11. The mean test-to-

Table 7 CSIRO 042/042, 060/060 and 075/075-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}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997)				*CSA-S136 (1994)*				*Eurocode 3 (1996)*			
042/042-G550	*Mean*	1.038	1.085	*042/042-G550*	*Mean*	0.974	1.019	*042/042-G550*	*Mean*	1.362	1.424
	No.	25	25		*No.*	25	25		*No.*	25	25
	S.D.	0.149	0.171		*S.D.*	0.141	0.162		*S.D.*	0.195	0,225
	C.o.V.	0.150	0.165		*C.o.V.*	0.151	0.166		*C.o.V.*	0.150	0.165
060/060-G550	*Mean*	0.986	0.994	*060/060-G550*	*Mean*	0.968	0.976	*060/060-G550*	*Mean*	1.294	1.304
	No.	27	27		*No.*	27	27		*No.*	27	27
	S.D.	0.128	0.131		*S.D.*	0.124	0.127		*S.D.*	0.169	0.172
	C.o.V.	0.136	0.138		*C.o.V.*	0.134	0.136		*C.o.V.*	0.136	0.138
075/075-G550	*Mean*	0.935	0.972	*075/075-G550*	*Mean*	1.014	1.053	*075/075-G550*	*Mean*	1.228	1.275
	No.	7	7		*No.*	7	7		*No.*	7	7
	S.D.	0.087	0.083		*S.D.*	0.128	0.121		*S.D.*	0.114	0.108
	C.o.V.	0.113	0.104		*C.o.V.*	0.155	0.141		*C.o.V.*	0.113	0.104

Table 8 CSIRO 080/080, 095/095 and 100/100-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}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997)				*CSA-S136 (1994)*				*Eurocode 3 (1996)*			
080/080-G550	*Mean*	0.983	1.016	*080/080-G550*	*Mean*	1.114	1.150	*080/080-G550*	*Mean*	1.290	1.333
	No.	34	34		*No.*	34	34		*No.*	34	34
	S.D.	0.086	0.095		*S.D.*	0.107	0.112		*S.D.*	0.113	0.125
	C.o.V.	0.090	0.097		*C.o.V.*	0.099	0.101		*C.o.V.*	0.090	0.097
095/095-G550	*Mean*	0.969	0.977	*095/095-G550*	*Mean*	1.133	1.143	*095/095-G550*	*Mean*	1.271	1.283
	No.	9	9		*No.*	9	9		*No.*	9	9
	S.D.	0.058	0.060		*S.D.*	0.149	0.152		*S.D.*	0.077	0.079
	C.o.V.	0.069	0.071		*C.o.V.*	0.152	0.153		*C.o.V.*	0.069	0.071
100/100-G550	*Mean*	0.964	1.010	*100/100-G550*	*Mean*	1.190	1.247	*100/100-G550*	*Mean*	1.265	1.326
	No.	10	10		*No.*	10	10		*No.*	10	10
	S.D.	0.082	0.077		*S.D.*	0.138	0.129		*S.D.*	0.107	0.101
	C.o.V.	0.096	0.086		*C.o.V.*	0.131	0.117		*C.o.V.*	0.096	0.086

Table 9 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}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997)				*CSA-S136 (1994)*				*Eurocode 3 (1996)*			
042/060-G550	*Mean*	0.866	0.908	*042/060-G550*	*Mean*	1.218	1.277	*042/060-G550*	*Mean*	1.556	1.632
	No.	3	3		*No.*	3	3		*No.*	3	3
	S.D.	0.121	0.151		*S.D.*	0.170	0.212		*S.D.*	0.217	0.271
	C.o.V.	-	-		*C.o.V.*	-	-		*C.o.V.*	-	-
042/080-G550	*Mean*	0.754	0.820	*042/080-G550*	*Mean*	1.065	1.159	*042/080-G550*	*Mean*	1.264	1.376
	No.	6	6		*No.*	6	6		*No.*	6	6
	S.D.	0.141	0.125		*S.D.*	0.199	0.177		*S.D.*	0.236	0.210
	C.o.V.	0.241	0.197		*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*	0.983	1.016	*042/100-G550*	*Mean*	1.106	1.144
	No.	10	10		*No.*	10	10		*No.*	10	10
	S.D.	0.143	0.130		*S.D.*	0.171	0.156		*S.D.*	0.192	0.175
	C.o.V.	0.197	0.174		*C.o.V.*	0.197	0.174		*C.o.V.*	0.197	0.174

Table 10 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}	*Specimen Type*	*Stat. Info.*	$P_{3.0t}/P_{up}$	P_{ut}/P_{up}
AS/NZS 4600 (1996) & AISI (1997)				*CSA-S136 (1994)*				*Eurocode 3 (1996)*			
042-G550/294-G250	*Mean*	0.770	0.794	*042-G550/294-G250*	*Mean*	0.778	0.802	*042-G550/294-G250*	*Mean*	0.991	1.021
	No.	6	6		*No.*	6	6		*No.*	6	6
	S.D.	0.082	0.056		*S.D.*	0.083	0.057		*S.D.*	0.106	0.072
	C.o.V.	0.138	0.091		*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*	0.776	0.873	*075-G550/294-G250*	*Mean*	1.109	1.248
	No.	3	3		*No.*	3	3		*No.*	3	3
	S.D.	0.158	0.195		*S.D.*	0.143	0.176		*S.D.*	0.204	0.251
100-G550/294-G250	*Mean*	0.865	1.027	*100-G550/294-G250*	*Mean*	0.778	0.924	*100-G550/294-G250*	*Mean*	1.112	1.320
	No.	3	3		*No.*	3	3		*No.*	3	3
	S.D.	0.109	0.027		*S.D.*	0.098	0.024		*S.D.*	0.140	0.034

Table 11 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 (1997)				*CSA-S136 (1994)*			
060/080-G550	*Mean*	0.893	0.986	*060/080-G550*	*Mean*	1.140	1.259
	No.	3	3		*No.*	3	3
	S.D.	0.173	0.128		*S.D.*	0.221	0.164
060/100-G550	*Mean*	0.836	0.973	*060/100-G550*	*Mean*	1.105	1.285
	No.	4	4		*No.*	4	4
	S.D.	0.052	0.115		*S.D.*	0.068	0.152
	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*	1.362	1.373
	No.	5	5		*No.*	5	5
	S.D.	0.011	0.006		*S.D.*	0.017	0.010
	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*	1.193	1.238
	No.	3	3		*No.*	3	3
	S.D.	0.049	0.046		*S.D.*	0.070	0.065
Eurocode 3 (1996)							
060/080-G550	*Mean*	1.488	1.642	*080/100-G550*	*Mean*	1.406	1.459
	No.	3	3		*No.*	3	3
	S.D.	0.288	0.214		*S.D.*	0.082	0.077
060/100-G550	*Mean*	1.415	1.647	*075/095-G550*	*Mean*	1.627	1.640
	No.	4	4		*No.*	5	5
	S.D.	0.088	0.195		*S.D.*	0.020	0.012
	C.o.V.	0.107	0.205		*C.o.V.*	0.018	0.010

predicted ultimate and serviceability load ratios, calculated using all of the design standards, for the 042/042-G550, 060/060-G550, 075/075-G550, 080/080-G550, 095/095-G550 and 100/100-G550 screwed connections were found to be above or slightly below unity. The mean test-to-predicted values for the Eurocode 3 Design Standard are all significantly conservative, i.e., the lowest mean ratio of $P_{3.0t}$ / P_{up} = 1.228 occurs for the 075/075-G550 test specimens. The AS/NZS 4600 and AISI *(1997)* Design Standards have a lowest mean $P_{3.0t}$ / P_{up} ratio of 0.964 for the 075/075-G550 test specimens. These results indicate that for single overlap screwed connections fabricated using the same thickness G550 sheet steels, the current design standards can be used to provide a reasonable estimate of the load carrying capacity (see Tables 7 and 8).

However, for tests where the connected G550 sheet steels are of different thickness, not all of the current design formulations provide an accurate estimate of the connection capacity. Mean serviceability test-to-predicted ratios, $P_{3.0t}$ / P_{up}, for the AS/NZS 4600 *(1996)* and AISI *(1997)* Design Standards range from 0.754 for the 042/080-G550 test specimens to 0.893 for the 060/080-G550 tests specimens. Mean ultimate test-to-predicted ratios, P_{ut} / P_{up}, for the same design standards are slightly higher with minimum and maximum values of 0.820 for the 042/080-G550 test specimens and 0.986 for the 060/080-G550 tests specimens, respectively (see Tables 9 and 11). The CSA-S136 Design Standard *(1994)* is conservative for connections composed of two different thickness G550 sheet steels, except for 042/100-G550 test specimens where the mean test-to-predicted serviceability ratio was slightly below 1.0, i.e., $P_{3.0t}$ / P_{up} = 0.983 (see Table 9). As previously found for connections fabricated using the same thickness G550 sheet steels the Eurocode 3 Design Standard *(1996)* can be used to provide a conservative estimate of the shear capacity for connections composed of two different thickness G550 sheet steels (see Tables 9 and 11).

Significantly different results occur in the prediction of connection capacity for test specimens composed of 2.94 mm G250 and thin G550 sheet steels. It is assumed that the 2.94 mm G250 sheet steel did not allow the screws to tilt during testing of these connections and bearing failure was forced to occur in the G550 sheet steel. The mean test-to-predicted ratios calculated using the Australian / New Zealand *(SA/SNZ, 1996)* and North American *(CSA, 1994; AISI, 1997)* Design Standards for the 042-G550/294-G250 screwed connections were found to be significantly unconservative, with $P_{3.0t} / P_{up}$ and P_{ut} / P_{up} ratios in the range of 0.770-0.802 (see Table 10). There is an improvement in test-to-predicted ratios for the thicker 075 and 100-G550 sheet steels, however the Australian / New Zealand and North American Design Standards remain unconservative. Only the European Design Standard *(Eurocode, 1996)* can be used to conservatively predict the capacity of the 042-G550/294-G250, 075-G550/294-G250 and 100-G550/294-G250 screwed connections. These results indicate that for a single overlap screwed connection where a thin G550 sheet steel is attached to a much thicker G250 sheet steel it appears that the bearing coefficients used in the Australian / New Zealand and North American Design Standards may need to be reduced (see (6) and Table 1).

5 Conclusions

The results of screwed connection tests completed for this paper and by the CSIRO *(Macindoe and Pham, 1996)* indicate that the current connection provisions set out in the CSA-S136 *(1994)* and Eurocode *(1996)* Design Standards can be used to predict the failure mode of screwed connections fabricated from thin G550 and G300 sheet steels. In only a limited number of cases does the use of the AS/NZS 4600 *(1996)* and AISI *(1997)* Design Standards result in incorrect failure mode predictions. These erroneous failure mode predictions are caused by the inclusion of an unnecessary stress reduction factor in the net section fracture formulation.

The Eurocode Design Standard *(1996)* provides an overly conservative estimate of the load carrying capacity of screwed connections composed of equal thickness G550 sheet steels which fail in the bearing/tilting mode, based on a bearing/tilting failure criterion for predicted loads. The AS/NZS 4600 *(1996)*, CSA-S136 *(1994)* and AISI *(1997)* 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.

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