ELSEVIER
Journal of Constructional Steel Research 51 (1999) 123–146
JOURNAL OF CONSTRUCTIONAL STEEL RESEARCH
www.elsevier.com/locate/jcsr

# Bolted connection design for sheet steels less than 1.0 mm thick

C.A. Rogers, G.J. Hancock*

*Department of Civil Engineering, University of Sydney, Sydney, NSW 2006 Australia*

Received 24 July 1998; received in revised form 22 December 1998; accepted 1 April 1999

**Abstract**

The results of recently completed shear tests indicate that the current connection provisions set out in the AS/NZS 4600, AISI and Eurocode cold formed steel design standards cannot be used to accurately predict the failure mode of bolted connections that are fabricated from thin G550 and G300 sheet steels. Furthermore, these design standards cannot be used to accurately determine the bearing resistance of bolted specimens based on a failure criterion for predicted loads. The measured variation in bearing resistance between thin 0.42 mm G550 sheet steels and typical 1.0 mm and thicker sheet steels has been used to develop a gradated bearing coefficient method, which is dependent on the thickness of the connected materials and the size of the bolt(s) used in the connection. It is recommended that the gradated bearing coefficient formulation, the unreduced net section resistance, and the Eurocode design method for end pull-out be used in the design of bolted connections. © 1999 Elsevier Science Ltd. All rights reserved.

*Keywords:* Bolts; Design; Connections; Standards; Steel structures; Thin sections

## 1. Introduction

Cold formed structural members are fabricated from sheet steels that must meet the material requirements prescribed in applicable national design standards. The Australian/New Zealand standard for cold-formed steel structures [1] (AS/NZS 4600)

* Corresponding author. Tel.: + 61-293-512144; fax: + 61-293-513343;
e-mail: hancock@civil.suioz.au


PII: S0143-974X(99)00018-8

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 that are cold reduced to thickness, engineers are required by design standards to use a yield stress and ultimate strength reduced to 75% of the minimum specified values. The American Iron and Steel Institute (AISI) Specification [2] 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 [1] and North American [2,3] design standards is based on an investigation of sheet steels by Dhalla and Winter [4,5] which did not include the thin, higher strength G550 sheet steels that are available today (see AS 1397 [6]).

Test results from the first phase of this study [7–9] reveal that the ability of G550 sheet steels to undergo deformation is dependent on the direction of load within the plane of the sheet, where transverse specimens exhibit the least amount of overall, local and uniform elongation. The G550 sheet steels which were tested do not meet the Dhalla and Winter [5] elongation and ultimate strength to yield stress ratio requirements regardless of direction, except for the uniform elongation of longitudinal coupon specimens.

The analysis of previously completed bolted connection tests that were fabricated from 0.42 and 0.60 mm G550 and G300 sheet steels [10,11] provides two significant results. Firstly, the low material ductility that was measured in coupon tests does not influence the net section fracture mode of failure. Secondly, the bearing capacity of thin sheet steels is overestimated when current design standards are used for the design of connections composed of either the G550 or G300 sheet steels. Additional bolted connection specimens that were composed of 0.80 and 1.00 mm G550 and G300 sheet steels have been tested and are described in this paper, and in more detail in Rogers and Hancock [12]. These tests have been used to develop a gradated bearing coefficient method which is dependent on the thickness of the connected materials and the diameter of the bolt(s) used in the connection. The measured variation in bearing resistance between the thin 0.42 mm G550 sheet steels and the typical 1.0 mm and thicker sheet steels is incorporated into a general bearing formulation. The additional bolted connections were dimensioned such that only bearing failure would occur, with test specimens milled from the longitudinal, transverse and diagonal directions of the sheet.

## 2. Background information

### 2.1. G550 and G300 sheet steels

The steels that were investigated as a part of this paper were produced using a process called cold reduction, which can be used to increase the strength and hardness, as well as to provide an accurate thickness for sheet steels and other steel products. This process causes the grain structure of cold reduced steels to elongate in the rolling direction, which produces a directional increase in material strength and a decrease in material ductility. The effects of cold working are cumulative, i.e. grain distortion increases with further cold working as a result of an increase in total dislocation density, however, it is possible to change the distorted grain structure and to control the steel properties through subsequent heat treatment. Various types of heat treatment exist and are used for different steel products. Both G300 and G550 sheet steels are stress relief annealed, i.e. the total dislocation density is reduced by annealing, although recrystallisation does not occur. Stress relief annealing involves heating the steel to below the recrystallisation temperature, holding the steel until the temperature is constant throughout its thickness, then cooling slowly. G300 sheet steels are annealed to a greater extent in comparison with G550 sheet steels [13]. This procedure results in near isotropic material properties for the mild sheet steels (G300) although some preferred grain orientation remains [7]. The G550 sheet steels that were 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.

The material property requirements for G300 or similar mild sheet steels and G550 or Grade E sheet steels are specified in Australia by AS 1397 [6] and in North America by the following ASTM Standards: A611 [14], A653 [15] and A792 [16]. Material property specifications for HSLA sheet steels can be found in ASTM Standard A653.

### *2.2. Cold formed steel bolted connection design provisions*

An overview of the design equations used for the prediction of bolted connection capacity is provided in this section. The nominal cross-section tension capacity 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 [1,3,17], except for the AISI Specification [2], as follows,

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

where $A_g$ is the area of the gross cross-section and $f_y$ is the yield or 0.2% proof 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, by the following equation,

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

where $A_n$ is the area of the net cross-section and $f_u$ is the ultimate strength. (Note: the formulae contained in Eqs. (1) and (2) have recently been approved for inclusion in the AISI Specification in AISI Ballot C/S96-66D [18]). The following material properties, 0.75 $f_y$ and 0.75 $f_u$, must be used in Eqs. (1)–(7) for the design of thin G550 sheet steels that do not meet the Dhalla and Winter [5] ductility requirements, using the Australia/New Zealand [1] and North American [2,3] design standards.

The Australia/New Zealand [1], USA [2] and European [17] design standards all have separate requirements for the net cross-section tension capacity at connections where washers are provided under both the bolt head and nut. This design provision was originally based on the analysis of bolted connections with washers that failed in a number of modes, including bearing [19–24] (see Rogers and Hancock [25]). The present form of the design equation for the AS/NZS 4600 and AISI design standards is as follows,

$$N_f = \left(1.0 - 0.9r + \frac{3rd}{s}\right)A_n f_u \leq A_n f_u \tag{3}$$

where $r$ is the ratio of the force transmitted by the bolt(s) divided by the tensile force in the member at that section, $d$ is the diameter of the bolt(s), and $s$ is the spacing of the bolts perpendicular to the line of the force, or for a single bolt the width of the sheet. The design formulation for the Eurocode design standard is similar to that presented in Eq. (3), however, $d$ is defined as the nominal diameter of the bolt hole. The CSA-S136 [3] design standard does not contain a stress reduction factor based on the number and position of bolts in the cross-section.

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

$$V_b = Ctdf_u \tag{4}$$

where $d$ is the nominal diameter of the bolt, $t$ is the thickness of the sheet steel and $C$ is a bearing coefficient. The Australian/New Zealand [1] and USA [2] design standards require that $C = 3$ for single lap shear connections where washers are used under both the bolt head and nut, whereas the European design standard [17] requires that $C = 2.5$. In the Canadian design standard [3] $C$ represents the stability of the hole edge based on the ratio of bolt diameter to sheet thickness, as listed in Table 1.

End pull-out capacity of a bolted connection is dependent on the length of two parallel lines which extend from the bolt hole in the direction of the applied force. This type of failure differs from block shear rupture because each bolt tears out along its own path. The nominal end pull-out capacity per bolt is given in Eq. (5) for the Australian/New Zealand [1] and USA [2] design standards.

$$V_f = tef_u \tag{5}$$

where $e$ is the distance measured parallel to the direction of applied force from the

Table 1
Factor $C$, for bearing resistance [3]

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

centre of a standard hole to the nearest edge of an adjacent hole or to the end of the connected part. The end pull-out capacity determined using the Eurocode design standard [17] is formulated in a similar fashion, however, the nominal capacity is reduced by a factor as follows,

$$V_f = tef_u/1.2 \tag{6}$$

The nominal end pull-out capacity per bolt of a connection designed using the CSA-S136 design standard [3] is determined as previously described for the net cross-section tension capacity.

$$V_f = A_n f_u \tag{7}$$

where the net cross-sectional area used for each bolt is defined as $A_n = 0.60 \cdot 2t(e - d_h/2)$, where $d_h$ is the diameter of the bolt hole.

## 3. Bolted connection tests and results

### *3.1. General*

A total of 18 additional single overlap bolted connection specimens [12] were tested at the University of Sydney, to complement the 158 bolted connection tests presented in Rogers and Hancock [10,11]. The main objective of this experimental testing phase was to develop a gradated bearing failure design provision for bolted connections that are fabricated from thin G550 and G300 sheet steels. Three different sheet steels were tested, including both G550 and G300 grades, i.e. 0.80 mm G550, 1.0 mm G550 and 0.80 mm G300, and used as a basis for comparison with the current design equations specified in the Australian/New Zealand [1], North American [2,3] and European [17] cold formed steel design standards. Testing of these steels was necessary to determine the variation in bearing coefficient with thickness. All steels were cold reduced to thickness, with an aluminum/zinc alloy (zincalume-AZ) coating and obtained from standard coils during normal rolling operations.

Single and double bolted tensile connections were dimensioned such that only bearing failure would occur while tested in shear (see Fig. 1). All test specimens had clipped ends to reduce the extent of out-of-plane curling (see Fig. 2 and Rogers and Hancock [10]). The possibility of bolt shear failure was eliminated by using M12 Grade 8.8 galvanised bolts with a nominal diameter of 12 mm and a bolt and nut assembly with integral washers (29.5 mmØ washer with 6 threads/cm). The results of previous tests of G550 sheet steel bolted connections have shown that no significant variation in ultimate bearing load occurs with the use of either an integral or conventional washer system [10].

Ultimate loads were obtained without the use of a deformation limit due to the initial slip of the connection and the extreme ultimate deformations of the sheet steel, in some instances between 10 and 30 mm. It could have been possible that the deformation limit of 3 mm specified in ECCS-TC7 [26] would only represent the slip load of the specimens, and the deformation limit of 6.35 mm specified by the

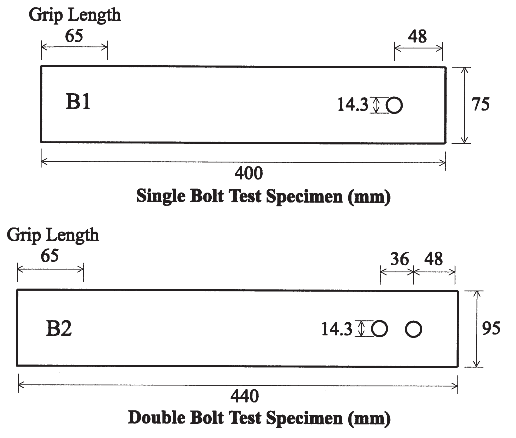


Fig. 1. Bolted connection specimens (nominal dimensions).

Research Council on Structural Connections [27] and the American Institute of Steel Construction [28,29] would represent a load which is not indicative of the full load carrying capacity of the bolted connection. The maximum tensile load which occurred prior to a connection displacement of 6.35 mm (excluding slip of the connection) was also recorded for all of the test specimens [12].

### *3.2. Basic material properties*

The basic material properties, i.e. yield stress and ultimate strength, for all of the sheet steels were obtained through the tensile testing of coated coupons according to ASTM A370 [30] recommendations (see Rogers and Hancock [7]). Static and dynamic material properties for each type of sheet steel, calculated using the base metal thickness are provided in Table 2.

All of the G550 sheet steels that were 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, and in the case of 1.0 mm G550 longitudinal specimens the low $f_u/f_y$ ratio. These G550 sheet steels do not meet the Dhalla and Winter [5] or current design standard [1–3] 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, $f_u/f_y \geq 1.08$ (see Rogers and Hancock [7]).

The material properties for the 0.80 and 1.0 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. The material properties of the G300 sheet steels are not dependent on direction within the plane of the sheet (see Table 2).

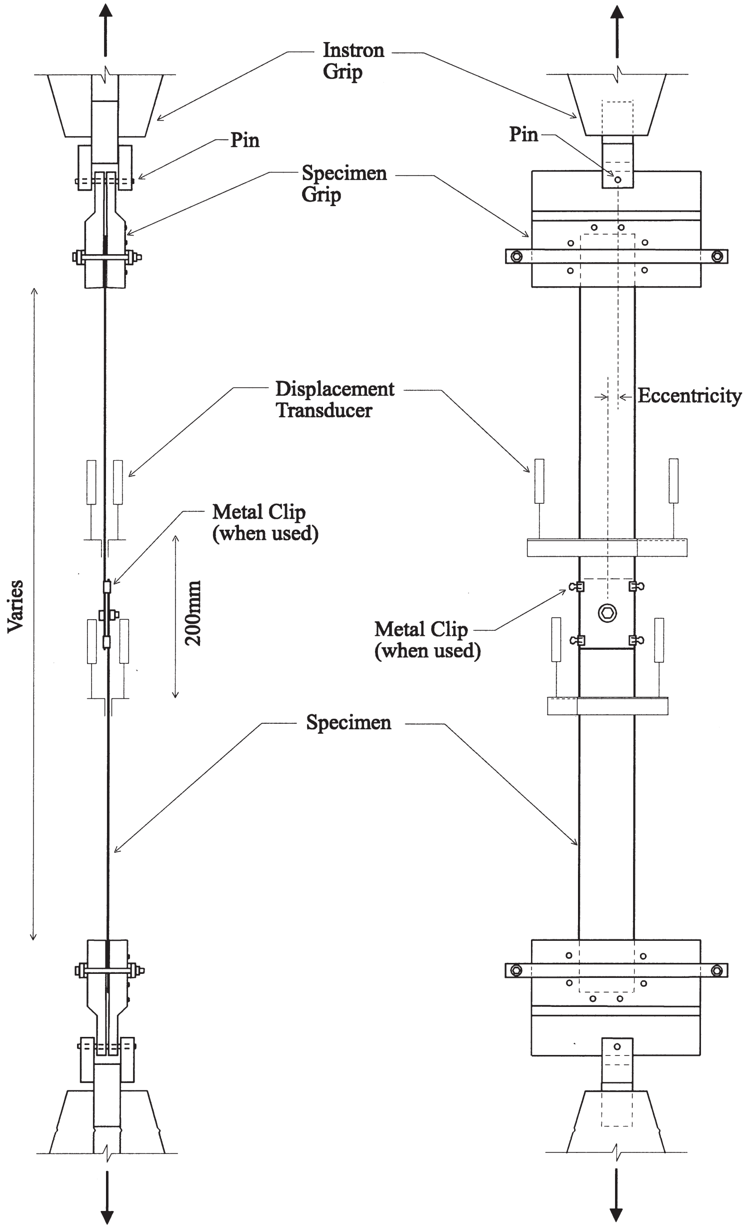


Fig. 2. Schematic drawing of bolted connection test set-up.

Table 2
Material properties of sheet steels (mean values)

| Specimen type | | $t_b$ (mm) | Base metal thickness | | |
|---|---|---|---|---|---|
| | | | $f_y{}^b$ (MPa) | $f_u{}^b$ (MPa) | $f_u/f_y{}^b$ |
| 0.80mm G550[a] | Longitudinal | 0.79 | 668/653 | 668/653 | 1.00/1.00 |
| | Transverse | 0.79 | 728/710 | 728/710 | 1.00/1.00 |
| | Diagonal | 0.79 | 675/657 | 675/657 | 1.00/1.00 |
| 1.0 mm G550[a] | 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 |
| 0.80mm G300[a] | 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 |

[a] Average of 3 coated coupon tests.
[b] Dynamic/Static values given.

### 3.3. Comparison of ultimate test-to-design standard predicted loads

Dynamic ultimate test loads, $P_{ut}$, were used in comparison with the predicted ultimate connection strengths, $P_{up}$, determined using the relevant design standards [1–3,17] without the $0.75f_y$ and $0.75f_u$ reduction. The lowest calculated load from the various connection equations within any one design standard is defined as the predicted mode of failure. Conclusions regarding the adequacy of design formulations which are based on a comparison of test-to-predicted ratios where the actual and predicted mode of failure do not match are invalid. Hence, detailed statistical information of the test-to-predicted ratios for the various design standards is not provided, however, overall values for the bolted connection specimens that are presented in this paper and in Rogers and Hancock [10,11] can be found in Table 3.

Only the CSA-S136 design standard [3] can be used to adequately predict the failure modes of the different bolted connection test specimens. The ratio of correct-to-incorrect failure mode prediction for the AS/NZS 4600 [1] and AISI [2] design standards is 92-84, where the majority of incorrect predictions were defined as net section failure when bearing failure occurred in the test specimen. The error in predicted failure mode can be attributed to design equations which overestimate and underestimate the bearing and net section fracture resistance, respectively. Bearing resistance equations are based on a large array of data which does not include a significant number of specimens with thickness less than 0.6 mm. The lack of specimens in this range has allowed the AS/NZS 4600 and AISI design standards to overlook the influence of thickness on bearing capacity. Test results from this research also show that it is not necessary to reduce the net section fracture capacity at connections as a function of the number of bolts and width of the specimen. Development of the net section stress reduction formulation that is contained in the AS/NZS 4600 and AISI design standards, was originally based on studies of bolted connections in which test specimens that failed by net section fracture, corner pull

Table 3
Design standard $P_{ut}/P_{up}$ statistical data for all tests (full $f_u$ used)

| Design standard | | $P_{ut}/P_{up}$ | Failure mode prediction |
|---|---|---|---|
| AS/NZS 4600 [1] and AISI [2] | | | |
| | Mean | 0.880 | Correct = 92 |
| | No. | 176 | Incorrect = 84 |
| | S.D. | 0.198 | |
| | C.o.V. | 0.227 | |
| CSA-S136[3] | | | |
| | Mean | 1.115 | Correct = 170 |
| | No. | 176 | Incorrect = 6 |
| | S.D. | 0.269 | |
| | C.o.V. | 0.243 | |
| Eurocode [17] | | | |
| | Mean | 0.959 | Correct = 149 |
| | No. | 176 | Incorrect = 27 |
| | S.D. | 0.178 | |
| | C.o.V. | 0.187 | |
| Proposed Method (see Section 4) | | | |
| | Mean | 1.077 | Correct = 167 |
| | No. | 176 | Incorrect = 9 |
| | S.D. | 0.149 | |
| | C.o.V. | 0.139 | |

out, end pull-out, as well as bearing were included [19–24]. It is likely that the net section stress reduction equation (Eq. (3)) models the bearing behaviour of bolted connections, due to the possible misidentification of bearing failures in specimens, where out-of-plane curling at the end of the specimen with fractures originating from the distorted sheet in front of the bolt occurred (see Rogers and Hancock [25]).

Use of the CSA-S136 design standard [3] provides a ratio of correct-to-incorrect failure mode prediction of 170-6. The six incorrectly predicted specimens were double bolted G300 tests for which net section failure occurred instead of the predicted bearing failure. The coefficient of $C = 2$ used in the CSA-S136 bearing equation for connections where $d/t \geq 15$ may be overly conservative for mild sheet steels. Use of the Eurocode Standard [17] gives a ratio of correct-to-incorrect failure mode prediction of 149-27. The large number of incorrect failure mode predictions is due to an overestimated bearing capacity and an underestimated net section fracture capacity, similar to that observed for the AS/NZS 4600 [1] and AISI [2] design standards.

### *3.4. Comparison of ultimate test-to-failure criterion predicted loads*

All of the bolted specimens that were tested for this research [10–12] were divided into separate categories according to the recorded failure mode, i.e. the three observed ultimate limit states; end pull-out, bearing and net section fracture (see Fig.

3). Thus, the predicted connection capacity that was used in comparison with the ultimate load obtained for each bolted connection was calculated using the design equation developed for that failure mode, e.g. all specimens that failed by bearing were compared with the predicted bearing capacity without the 0.75 reduction factor.

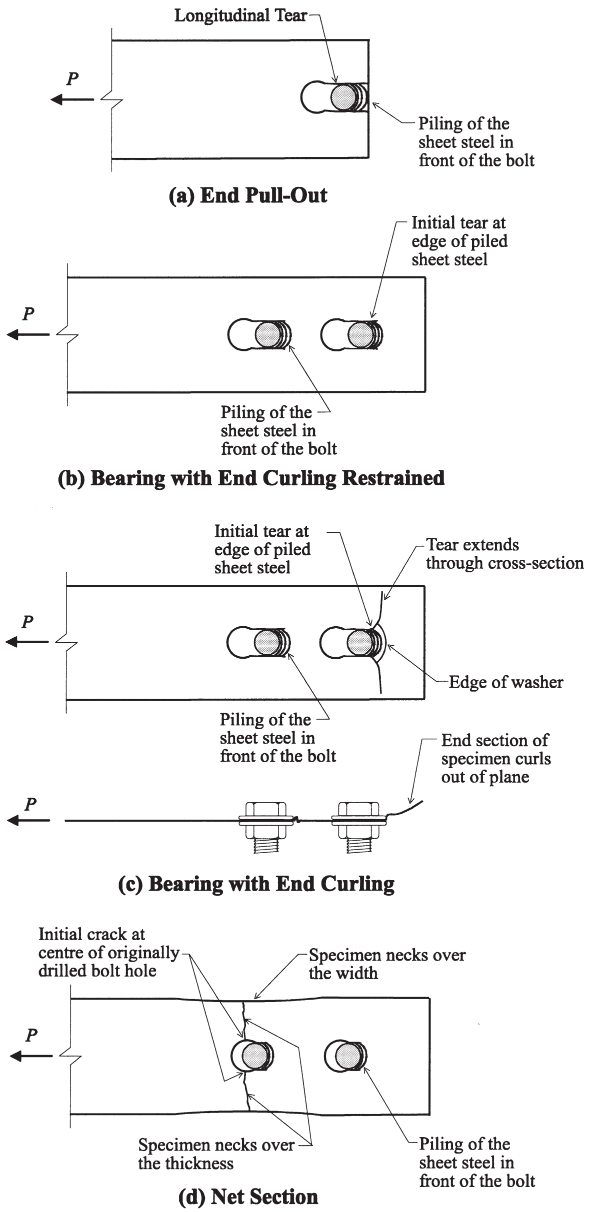


Fig. 3. Bolted connection failure patterns

This type of failure based criterion comparison reveals the accuracy of each individual design equation by eliminating the influence of the remaining bolted connection design provisions, e.g. net section fracture may be predicted using the relevant design standards when the test specimen was observed to have failed by bearing. Statistical results for all of the bolted connection test specimens that are contained in Rogers and Hancock [10,11] and in this paper can be found in Table 4. Statistical results for each material type, design standard and failure mode are provided for the 0.80 mm G550, 1.0 mm G550 and 0.80 mm G300 sheet steels in Table 5 and for the previously tested bolted connections [10,11] in Tables 6–8.

The overall failure based criterion results indicate that the AS/NZS 4600 [1] and AISI [2] design standards can both be used to conservatively predict the net section failure loads of bolted connections. However, the calculated end pull-out resistance is found to be unconservative with a mean test-to-predicted ratio of 0.894. The connection resistance of bolted specimens which failed in bearing is inaccurately modelled by the existing AS/NZS 4600 and AISI design provisions. The resulting mean test-to-predicted ratios are significantly unconservative, with a mean $P_{ut}/P_{up}$ value of 0.726.

The ultimate connection resistance of bolted specimens determined using the Eurocode design standard [17] can be more accurately calculated in comparison with the AS/NZS 4600 [1] and AISI [2] design standards. End pull-out failure can be

Table 4
Failure based criterion $P_{ut}/P_{up}$ statistical data for all tests (full $f_u$ used)

| Design standard | | End pull-out $P_{ut}/P_{up}$ | Bearing $P_{ut}/P_{up}$ | Net-section $P_{ut}/P_{up}$ |
|---|---|---|---|---|
| AS/NZS 4600 [1] and AISI [2] | | | | |
| | Mean | 0.894 | 0.726 | 1.137 |
| | No. | 36 | 99 | 26 |
| | S.D. | 0.131 | 0.149 | 0.054 |
| | C.o.V. | 0.150 | 0.207 | 0.050 |
| CSA-S136 [3] | | | | |
| | Mean | 1.313 | 1.074 | 1.007 |
| | No. | 36 | 99 | 26 |
| | S.D. | 0.413 | 0.217 | 0.048 |
| | C.o.V. | 0.324 | 0.204 | 0.050 |
| Eurocode [17] | | | | |
| | Mean | 1.072 | 0.871 | 1.075 |
| | No. | 36 | 99 | 26 |
| | S.D. | 0.157 | 0.179 | 0.050 |
| | C.o.V. | 0.150 | 0.207 | 0.048 |
| Proposed method (see Section 4) | | | | |
| | Mean | 1.072 | 1.089 | 1.007 |
| | No. | 36 | 99 | 26 |
| | S.D. | 0.157 | 0.163 | 0.048 |
| | C.o.V. | 0.150 | 0.151 | 0.050 |

Note: Statistical data excludes eccentrically loaded bolted connection tests [10].

Table 5
Failure based criterion $P_{ut}/P_{up}$ statistical data for additional tests (full $f_u$ used)

| Design standard | | 0.80 mm G550 $P_{ut}/P_{up}$ | 1.0 mm G550 $P_{ut}/P_{up}$ | 0.80 mm G300 $P_{ut}/P_{up}$ |
|---|---|---|---|---|
| AS/NZS 4600 [1] and AISI [2] | | | | |
| Bearing | Mean | 0.847 | 0.862 | 1.068 |
| | No. | 6 | 6 | 6 |
| | S.D. | 0.084 | 0.100 | 0.140 |
| | C.o.V. | 0.129 | 0.151 | 0.170 |
| CSA-S136 [3] | | | | |
| Bearing | Mean | 1.270 | 1.045 | 1.602 |
| | No. | 6 | 6 | 6 |
| | S.D. | 0.127 | 0.122 | 0.211 |
| | C.o.V. | 0.129 | 0.151 | 0.170 |
| Eurocode [17] | | | | |
| Bearing | Mean | 1.016 | 1.034 | 1.282 |
| | No. | 6 | 6 | 6 |
| | S.D. | 0.101 | 0.121 | 0.169 |
| | C.o.V. | 0.129 | 0.151 | 0.170 |
| Proposed Method (see Section 4) | | | | |
| Bearing | Mean | 1.024 | 0.927 | 1.292 |
| | No. | 6 | 6 | 6 |
| | S.D. | 0.102 | 0.108 | 0.170 |
| | C.o.V. | 0.129 | 0.151 | 0.170 |

conservatively predicted based on the results provided in Table 4. Net section fracture prediction behaviour remains conservative, although not to the extent exhibited by the AS/NZS 4600 and AISI design standards. However, the bearing resistance formulation remains significantly unconservative with a mean test-to-predicted ratio of 0.871, determined using all of the bearing failure test specimens.

The CSA-S136 design standard [3] provides overly conservative predictions of the end pull-out capacity for the sheet steels that were tested. Net section fracture connection resistance can be accurately modelled using the net cross-sectional area and the ultimate material strength without a stress reduction factor. A dramatic improvement in the ability to predict the ultimate bearing resistance of the sheet steels that were tested for this research project occurs with the use of the CSA-S136 design standard. The mean test-to-predicted ratio increases to a conservative value of 1.074. The consistently unconservative mean test-to-predicted ratios for bearing failure, determined using the Eurocode [17], AS/NZS 4600 [1] and AISI [2] design standards, indicates that a gradated bearing coefficient method is necessary for the accurate design of bolted connections that are composed of thin sheet steels.

The results of the additional bolted connection specimens that were tested for this paper reveal that the AS/NZS 4600 [1] and AISI [2] design standards remain unconservative when used to predict the bearing failure loads of the 0.80 and 1.00 mm G550 sheet steels. However, the bearing resistance of the 0.80 mm G300 test specimens can be accurately calculated; which is most likely due to the use of mild

Table 6
Failure based criterion $P_{ut}/P_{up}$ statistical data for 0.42 mm G550 sheet steel connections (full $f_u$ used)

| Failure mode | | Longitudinal $P_{ut}/P_{up}$ | Transverse $P_{ut}/P_{up}$ | Diagonal $P_{ut}/P_{up}$ | Failure mode | | Longitudinal $P_{ut}/P_{up}$ | Transverse $P_{ut}/P_{up}$ | Diagonal $P_{ut}/P_{up}$ |
|---|---|---|---|---|---|---|---|---|---|
| AS/NZS 4600 [1] and AISI [2] | | | | | Eurocode [17] | | | | |
| End pull-out | Mean | 0.960 | 0.795 | 0.911 | End pull-out | Mean | 1.152 | 0.954 | 1.093 |
| | No. | 6 | 6 | 6 | | No. | 6 | 6 | 6 |
| | S.D. | 0.070 | 0.166 | 0.147 | | S.D. | 0.084 | 0.199 | 0.176 |
| | C.o.V. | 0.094 | 0.269 | 0.208 | | C.o.V. | 0.094 | 0.269 | 0.208 |
| Bearing | Mean | 0.661 | 0.591 | 0.622 | Bearing | Mean | 0.793 | 0.710 | 0.746 |
| | No. | 14 | 14 | 14 | | No. | 14 | 14 | 14 |
| | S.D. | 0.049 | 0.048 | 0.056 | | S.D. | 0.059 | 0.058 | 0.067 |
| | C.o.V. | 0.081 | 0.089 | 0.097 | | C.o.V. | 0.081 | 0.089 | 0.097 |
| Net section | Mean | 1.202 | 1.089 | 1.154 | Net section | Mean | 1.141 | 1.029 | 1.091 |
| fracture | No. | 3 | 4 | 4 | fracture | No. | 3 | 4 | 4 |
| | S.D. | 0.051 | 0.046 | 0.010 | | S.D. | 0.063 | 0.034 | 0.016 |
| | C.o.V. | 0.073 | 0.073 | 0.015 | | C.o.V. | 0.095 | 0.057 | 0.025 |
| CSA-S136 [3] | | | | | Proposed Method (see Section 4) | | | | |
| End pull-out | Mean | 1.391 | 1.180 | 1.391 | End pull-out | Mean | 1.152 | 0.954 | 1.093 |
| | No. | 6 | 6 | 6 | | No. | 6 | 6 | 6 |
| | S.D. | 0.384 | 0.463 | 0.646 | | S.D. | 0.084 | 0.199 | 0.176 |
| | C.o.V. | 0.357 | 0.507 | 0.599 | | C.o.V. | 0.094 | 0.269 | 0.208 |
| Bearing | Mean | 0.991 | 0.887 | 0.933 | Bearing | Mean | 1.101 | 0.986 | 1.036 |
| | No. | 14 | 14 | 14 | | No. | 14 | 14 | 14 |
| | S.D. | 0.074 | 0.073 | 0.084 | | S.D. | 0.082 | 0.081 | 0.093 |
| | C.o.V. | 0.081 | 0.089 | 0.097 | | C.o.V. | 0.081 | 0.089 | 0.097 |
| Net section | Mean | 1.088 | 0.977 | 1.036 | Net section | Mean | 1.088 | 0.977 | 1.036 |
| fracture | No. | 3 | 4 | 4 | fracture | No. | 3 | 4 | 4 |
| | S.D. | 0.072 | 0.027 | 0.026 | | S.D. | 0.072 | 0.027 | 0.026 |
| | C.o.V. | 0.114 | 0.048 | 0.043 | | C.o.V. | 0.114 | 0.048 | 0.043 |

Table 7
Failure based criterion $P_{ut}/P_{up}$ statistical data for 0.60 mm G550 sheet steel connections (full $f_u$ used)

| Failure mode | | Longitudinal $P_{ut}/P_{up}$ | Transverse $P_{ut}/P_{up}$ | Diagonal $P_{ut}/P_{up}$ | Failure mode | | Longitudinal $P_{ut}/P_{up}$ | Transverse $P_{ut}/P_{up}$ | Diagonal $P_{ut}/P_{up}$ |
|---|---|---|---|---|---|---|---|---|---|
| AS/NZS 4600 [1] and AISI [2] | | | | | Eurocode [17] | | | | |
| End pull-out | Mean | 0.841 | 0.729 | 0.845 | End pull-out | Mean | 1.009 | 0.875 | 1.014 |
| | No. | 3 | 3 | 3 | | No. | 3 | 3 | 3 |
| | S.D. | 0.061 | 0.020 | 0.045 | | S.D. | 0.074 | 0.024 | 0.054 |
| Bearing | Mean | 0.718 | 0.636 | 0.693 | Bearing | Mean | 0.862 | 0.763 | 0.832 |
| | No. | 7 | 7 | 7 | | No. | 7 | 7 | 7 |
| | S.D. | 0.048 | 0.037 | 0.066 | | S.D. | 0.058 | 0.044 | 0.079 |
| | C.o.V. | 0.082 | 0.071 | 0.116 | | C.o.V. | 0.082 | 0.071 | 0.116 |
| Net section fracture | Mean | 1.140 | 1.127 | 1.138 | Net section fracture | Mean | 1.077 | 1.065 | 1.074 |
| | No. | 2 | 2 | 2 | | No. | 2 | 2 | 2 |
| | S.D. | 0.032 | 0.058 | 0.048 | | S.D. | 0.012 | 0.036 | 0.027 |
| CSA-S136 [3] | | | | | Proposed Method (see Section 4) | | | | |
| End pull-out | Mean | 1.215 | 1.060 | 1.232 | End pull-out | Mean | 1.009 | 0.875 | 1.014 |
| | No. | 3 | 3 | 3 | | No. | 3 | 3 | 3 |
| | S.D. | 0.330 | 0.320 | 0.390 | | S.D. | 0.074 | 0.024 | 0.054 |
| Bearing | Mean | 1.077 | 0.954 | 1.040 | Bearing | Mean | 1.096 | 0.971 | 1.058 |
| | No. | 7 | 7 | 7 | | No. | 7 | 7 | 7 |
| | S.D. | 0.072 | 0.055 | 0.098 | | S.D. | 0.073 | 0.056 | 0.100 |
| | C.o.V. | 0.082 | 0.071 | 0.116 | | C.o.V. | 0.082 | 0.071 | 0.116 |
| Net section fracture | Mean | 1.023 | 1.011 | 1.021 | Net section fracture | Mean | 1.023 | 1.011 | 1.021 |
| | No. | 2 | 2 | 2 | | No. | 2 | 2 | 2 |
| | S.D. | 0.004 | 0.019 | 0.011 | | S.D. | 0.004 | 0.019 | 0.011 |

Table 8
Failure based criterion $P_{ut}/P_{up}$ statistical data for 0.60 mm G300 sheet steel connections (full $f_u$ used)

| Failure mode | | Longitudinal $P_{ut}/P_{up}$ | Transverse $P_{ut}/P_{up}$ | Diagonal $P_{ut}/P_{up}$ | Failure mode | | Longitudinal $P_{ut}/P_{up}$ | Transverse $P_{ut}/P_{up}$ | Diagonal $P_{ut}/P_{up}$ |
|---|---|---|---|---|---|---|---|---|---|
| AS/NZS 4600 [1] and AISI [2] | | | | | Eurocode [17] | | | | |
| End pull-out | Mean | 0.990 | 0.994 | 0.997 | End pull-out | Mean | 1.188 | 1.192 | 1.196 |
| | No. | 3 | 3 | 3 | | No. | 3 | 3 | 3 |
| | S.D. | 0.096 | 0.078 | 0.082 | | S.D. | 0.115 | 0.093 | 0.099 |
| Bearing | Mean | 0.798 | 0.804 | 0.842 | Bearing | Mean | 0.957 | 0.964 | 1.011 |
| | No. | 6 | 6 | 6 | | No. | 6 | 6 | 6 |
| | S.D. | 0.123 | 0.135 | 0.141 | | S.D. | 0.148 | 0.162 | 0.169 |
| | C.o.V. | 0.199 | 0.217 | 0.215 | | C.o.V. | 0.199 | 0.217 | 0.215 |
| Net section | Mean | 1.124 | 1.147 | 1.120 | Net section | Mean | 1.062 | 1.083 | 1.058 |
| fracture | No. | 3 | 3 | 3 | fracture | No. | 3 | 3 | 3 |
| | S.D. | 0.079 | 0.067 | 0.066 | | S.D. | 0.068 | 0.059 | 0.061 |
| CSA-S136 [3] | | | | | Proposed Method (see Section 4) | | | | |
| End pull-out | Mean | 1.424 | 1.440 | 1.467 | End pull-out | Mean | 1.188 | 1.192 | 1.196 |
| | No. | 3 | 3 | 3 | | No. | 3 | 3 | 3 |
| | S.D. | 0.349 | 0.364 | 0.402 | | S.D. | 0.115 | 0.093 | 0.099 |
| Bearing | Mean | 1.197 | 1.205 | 1.264 | Bearing | Mean | 1.239 | 1.248 | 1.309 |
| | No. | 6 | 6 | 6 | | No. | 6 | 6 | 6 |
| | S.D. | 0.185 | 0.202 | 0.211 | | S.D. | 0.191 | 0.210 | 0.218 |
| | C.o.V. | 0.199 | 0.217 | 0.215 | | C.o.V. | 0.199 | 0.217 | 0.215 |
| Net section | Mean | 0.966 | 0.986 | 0.963 | Net section | Mean | 0.966 | 0.986 | 0.963 |
| fracture | No. | 3 | 3 | 3 | fracture | No. | 3 | 3 | 3 |
| | S.D. | 0.028 | 0.022 | 0.018 | | S.D. | 0.028 | 0.022 | 0.018 |

sheet steel data in the development of the current bearing design expressions. The CSA-S136 [3] and Eurocode [17] design standards can be used to conservatively predict the load carrying capacity of bolted connections that were composed of the 0.80 and 1.00 mm sheet steels.

The results of the previously tested 0.42 and 0.60 mm G550 sheet steel bolted connections [10,11] show that the bearing resistance is dependent on the thickness of the connected materials. The thinnest sheet steels which were tested provide the most unconservative test-to-predicted ratios for bearing failure, e.g. $P_{ut}/P_{up} = 0.591$ for the transverse 0.42 mm G550 test specimens which failed in bearing (see Table 6). In addition, the increased test-to-predicted ratios for the mild G300 sheet steels indicate that the bearing resistance coefficient may also be dependent on the material properties of the sheet steels.

## 4. Proposed design provisions for bolted connections

### *4.1. Basis of the proposed method*

Unconservative predictions of connection bearing capacity have demonstrated a need for a gradated bearing coefficient that is dependent on the stability of the edge of the bolt hole. These unsatisfactory results occur for bolted test specimens where thin sheet steels ($t < 1.0$ mm) are connected and loaded in shear; as shown for the failure based criterion test-to-predicted results that were calculated using the AS/NZS 4600 [1], AISI [2] and Eurocode [17] design standards, without the 0.75 reduction factor, for the 0.42 mm G550 test specimens in Table 6, the 0.60mm G550 test specimens in Table 7, the 0.60 mm G300 test specimens in Table 8, as well as the 0.80 mm G550 and 1.0 mm G550 test specimens (which all failed in bearing) in Table 5. A proposed method that relies on the ratio of bolt diameter to sheet thickness, $d/t$, to accommodate for the change in bearing behaviour of thin sheet steels is presented in this section.

This proposed method includes the gross yielding, Eq. (8), and the net section fracture, Eq. (9), failure provisions that are contained in the CSA-S136 [3] design standard, i.e. no stress reduction factor is used. Calculation of the end pull-out resistance follows the procedure given in the Eurocode design standard [17], Eq. (10). The European formulation is recommended because it provides a better fit to the bolted connection test data that failed by end pull-out. The recommended equations for gross yielding failure, net section fracture and end pull-out failure are as follows:

$$N_t = A_g f_y \tag{8}$$

where $A_g$ is the area of the gross cross-section and $f_y$ is the yield or 0.2% proof stress.

$$N_t = A_n f_u \tag{9}$$

where $A_n$ is the area of the net cross-section and $f_u$ is the ultimate strength.

$$V_f = tef_u/1.2 \tag{10}$$

where $t$ is the thickness of the thinnest connected part and $e$ is the distance measured parallel to the direction of applied force from the centre of a standard hole to the nearest edge of an adjacent hole or to the end of the connected part.

Modification to the existing bolted connection design provisions was made to the bearing formulation. Bearing stress ratios, $f_{bu}/f_u$, for all of the bolted connection test specimens that failed by bearing are illustrated in Fig. 4(a,b). 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 [3], is proposed. The maximum and minimum bearing coefficients for the bolted connections that have washers adjacent to the bolt head and nut are 3.0 and 1.8, respectively; which correspond to the results illustrated in Fig. 4(a,b).

At present, the bearing coefficient that is contained in the AS/NZS 4600 [1] and AISI [2] design standards is a constant $C = 3.0$ for single shear bolted connections with washers under the head and nut. The Eurocode design standard [17] also specifies a constant bearing coefficient of $C = 2.5$ for bolted connections. The CSA-S136

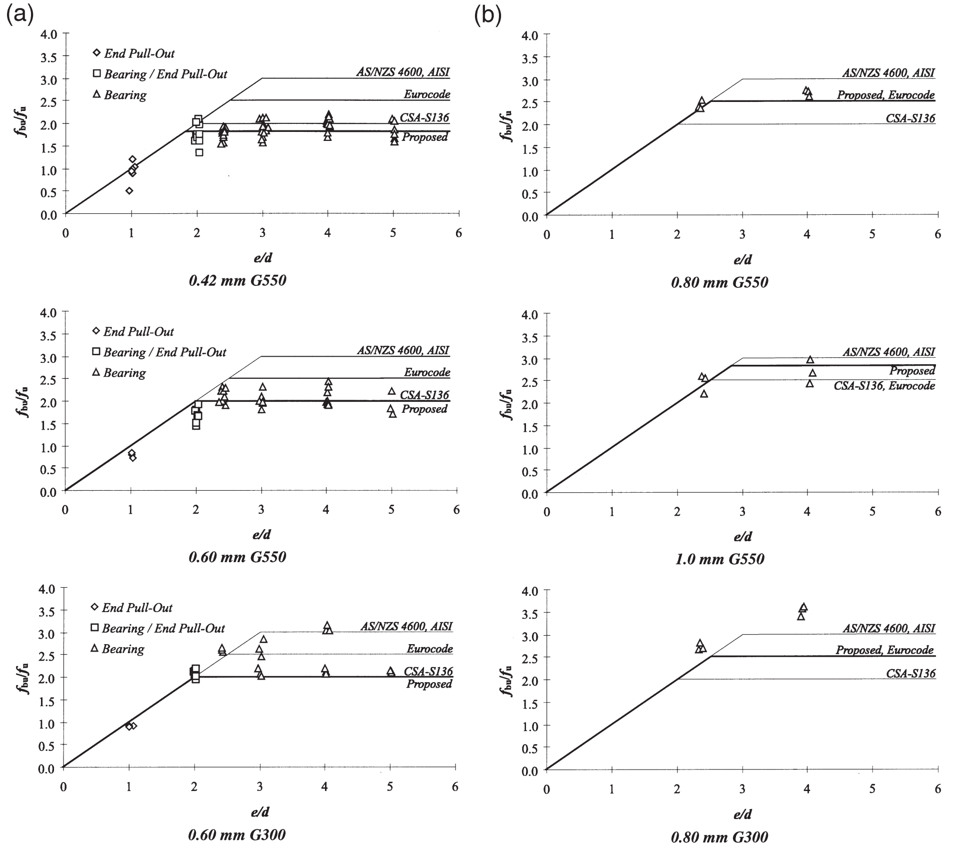


Fig. 4. (a) Proposed bolted connection bearing design formulation (full $f_n$ used). (b) Proposed bolted connection bearing design formulation (full $f_u$ used).

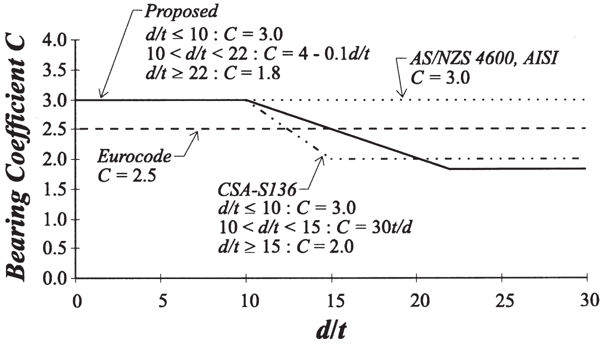


Fig. 5. Existing and proposed bearing coefficients for bolted connections.

design standard [3] requires that the bearing coefficient vary depending on the ratio of $d/t$, as shown in Fig. 5. The proposed method contains a variable bearing coefficient which is also dependent on $d/t$, however, the minimum possible value is lowered to 1.8 and the rate of change of the bearing coefficient is modified accordingly.

The proposed bearing formulation specifies that for a single shear connection the nominal bearing capacity is calculated as follows,

$$V_b = Ctdf_u \tag{11}$$

where $t$ and $f_u$ are the thickness and tensile strength of the member, and $C$ is the variable bearing coefficient as presented in Table 9.

### *4.2. Comparison of the proposed method with existing design standards*

Statistical information that was calculated using the existing design standards [1–3,17], as well as the proposed method, for the bolted connection tests that were completed for this research project [10–12] can be found in Tables 4–8. A distinct improvement in the mean values of the test-to-predicted ratios comparing the proposed method with the AS/NZS 4600 [1], AISI [2] and Eurocode [17] design standards is evident for the specimens where thin sheet steels are connected, as shown in Tables 6–8. In the case of the 0.42 mm G550 test specimens the mean $P_{ut}/P_{up}$ ratios for the longitudinal, transverse and diagonal directions improve from 0.661, 0.591 and 0.622 for the AS/NZS 4600 and AISI design standards to 1.101, 0.986

Table 9
Proposed factor $C$, for bearing resistance

| $d/t$ | $C$ |
|---|---|
| $d/t \leq 10$ | 3.0 |
| $10 < d/t < 22$ | 4.0–0.1 $d/t$ |
| $d/t \geq 22$ | 1.8 |

and 1.036 for the proposed method (see Table 6). A dramatic improvement in the mean test-to-predicted ratios also occurs for the 0.60 mm G550 test specimens, where for the AS/NZS 4600 and AISI design standards $P_{ut}/P_{up}$ ratios of 0.718, 0.636 and 0.693 were calculated for the longitudinal, transverse and diagonal specimens, respectively, and for the proposed method corresponding ratios of 1.096, 0.971 and 1.058 were determined (see Table 7). An improvement in the mean $P_{ut}/P_{up}$ ratios also occurs for the 0.60 mm G300 test specimens listed in Table 8, however, the resulting test-to-predicted ratios rise above 1.0 due to the dependence of bearing resistance on material properties as well as the $d/t$ ratio.

The $P_{ut}/P_{up}$ ratios that were determined using the AS/NZS 4600 [1] and AISI [2] design standards, as well as the proposed method, for all of the bolted connection test specimens that are included in this paper are provided in Fig. 6. These figures

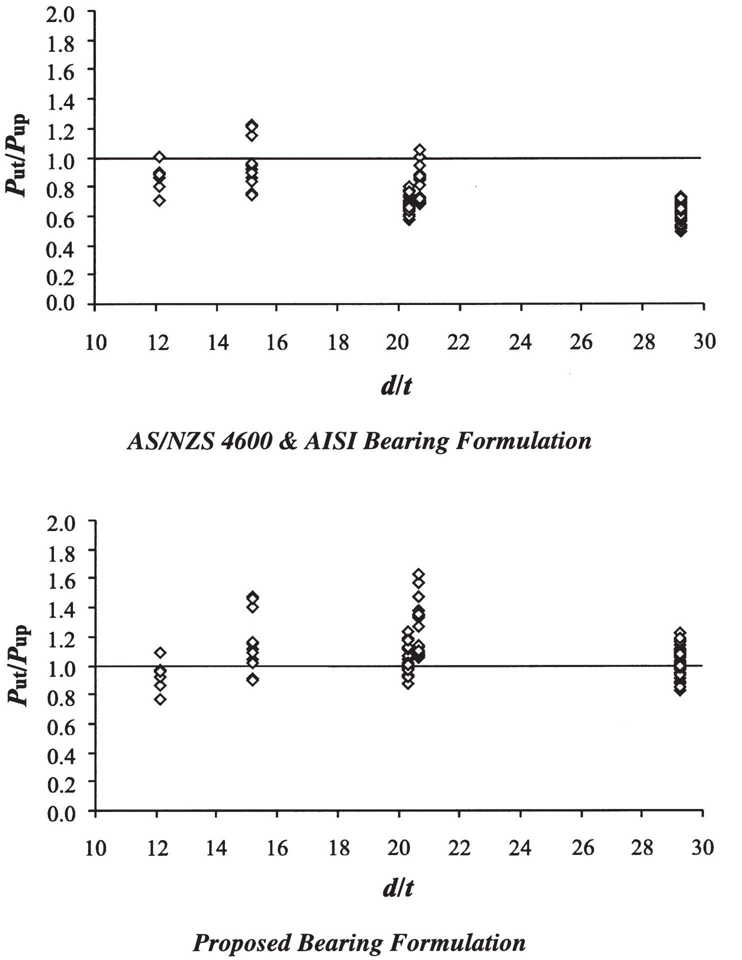


Fig. 6. Bearing test specimen test-to-predicted results, $P_{ut}/P_{up}$ vs $d/t$ (full $f_u$ used).

show the expected scatter of results typical for large data bases of bolted connection results. More importantly, these graphs illustrate an overall improvement in mean $P_{ut}/P_{up}$ values, especially for $d/t > 20$, when the predicted ultimate connection capacities are based on the proposed method.

The resulting $P_{ut}/P_{up}$ ratios for the G300 sheet steel bolted connection specimens using the proposed gradated bearing resistance method are conservative in comparison to the ratios for similar thickness G550 sheet steels. This result is caused by the dependence of the bearing coefficient on the material properties, as well as the thickness of the connected sheet steels. An attempt to model the relationship between the bearing resistance and the material properties, along with other variables, has been completed by Zadanfarrokh and Bryan [31], as well as Bryan [32]. The authors of this paper have not included a material property dependence in the gradated bearing formulation to limit the complexity of the recommended formulation. The bearing resistance of bolted connections constructed of G300 and other mild sheet steels can be conservatively predicted using the recommended formulation, hence, design predictions of connection capacity will be safe. It is the unconservative behaviour observed for bolted connections constructed of thin G550 sheet steels that needs to be accommodated for in design.

### 4.3. AISI calibrated resistance (capacity) factors, $\phi$

The reliability of a structure at various limit states can be estimated by means of a first and second order moment (FOSM), i.e. mean and coefficient of variation, reliability analysis method. Standards which incorporate a limit states philosophy as a basis for design, e.g. Australia/New Zealand AS/NZS 4600 [1], are dependent on load, $\gamma_i$, and resistance (capacity), $\phi$, factors to account for uncertainties and variabilities associated with loads, analysis, the limit state model, material properties, geometry and fabrication. Limit states design provides a higher degree of reliability in comparison to allowable stress design because of the ability to account for the variance in different types of loads, e.g. dead and wind, and structural resistance [33].

The safety index, $\beta$, is related to the resistance (capacity) factor, $\phi$, as follows,

$$\beta = \frac{\ln((M_m \cdot F_m \cdot P_m)/(Q_f \phi))}{\sqrt{V_M^2 + V_F^2 + V_P^2 + 0.21^2}} \tag{12}$$

where $Q_f = 0.691$, 0.657 and 0.683 for the Australian and Canadian, New Zealand and USA and European reliability formulations, respectively, and where $M_m$, $F_m$, $P_m$, $V_M$, $V_F$, and $V_P$ are mean values and coefficients of variation for material properties, fabrication variables and design equations, respectively. Resistance (capacity) factors, $\phi$, may be calculated for the connection expressions of each design standard by rearranging Eq. (12), substituting an appropriate value for the target reliability index, $\beta_o$, and solving for $\phi$. The AISI commentary [33] recommends that a $\beta_o$ of 3.5 be used for connections.

#### 4.3.1. Limit states calibration of the proposed method

The resistance equations for end pull-out, bearing and net section failure that are contained in the proposed method for bolted connection design were calibrated according to the procedure specified in the AISI commentary [33]. All of the bolted connection test data that is included in this paper was used to provide the necessary statistical information (see Table 10). Calibration of the proposed method for end pull-out, bearing and net section 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 [1–3].

Resistance (capacity) factors that were determined using the Australian [34], New Zealand [35] and USA [2] dead and live load factors with $P_{ut}/P_{up}$ ratios calculated using all of the bolted connection specimens that were tested for this research exceed the required $\phi = 0.60$ for the end pull-out and bearing failure equations. Similarly, use of the proposed equation for net section fracture yields resistance (capacity) factors which exceed the required $\phi = 0.765$ (0.75 USA) for $\beta_o = 3.5$. Calculated

Table 10
AISI derived resistance (capacity) factors, $\phi$, for the proposed bolted connection design method

| Data type | Stat. Info. | End pull-out | Bearing | Net section |
|---|---|---|---|---|
| Test Data $P_{ut}/P_{up}$ | Mean | 1.072 | 1.089 | 1.007 |
| | No. | 36 | 99 | 26 |
| | S.D. | 0.157 | 0.163 | 0.048 |
| | C.o.V. | 0.150 | 0.151 | 0.050 |
| Calibration Data $P_{ut}/P_{up}$ | $P_m$ | 1.072 | 1.089 | 1.007 |
| | $P_m$ (with $0.75f_u$) | 1.430 | 1.452 | 1.342 |
| | $V_P$ | 0.150 | 0.151 | 0.050 |
| | $\beta_o$ | 3.5 | 3.5 | 3.5 |
| **Load comparison** | **Res. Fact.** | **End pull-out** | **Bearing** | **Net section** |
| $P_{ut}/P_{up}$Australia [1] | $\phi$ (calculated) | 0.80 | 0.81 | 0.87 |
| | $\phi$ (calc. 0.75 $f_u$) | 1.42 | 1.44 | 1.54 |
| | $\phi$ (current) | 0.60 | 0.60 | 0.765[a] |
| $P_{ut}/P_{up}$New Zealand [1] and USA [2] | $\phi$ (calculated) | 0.84 | 0.85 | 0.91 |
| | $\phi$ (calc. 0.75 $f_u$) | 1.50 | 1.52 | 1.62 |
| | $\phi$ (current) | 0.60 | 0.60 | 0.765[a] (0.75 US) |
| $P_{ut}/P_{up}$ Canada [3] | $\phi$ (calculated) | 0.80 | 0.81 | 0.87 |
| | $\phi$ (calc. 0.75 $f_u$) | 1.42 | 1.44 | 1.54 |
| | $\phi$ (current) | 0.75 | 0.75 | 0.75 |
| $P_{ut}/P_{up}$ Europe [17] | $\phi$ (calculated) | 0.81 | 0.82 | 0.88 |
| | $\phi$ (calc. 0.75 $f_u$) | 1.44 | 1.46 | 1.56 |
| | $1/\gamma_{M2}$ (current) | 0.80 | 0.80 | 0.80 |

[a] AS/NZS 4600 [1] $\phi = 0.85 \times 0.90 = 0.765$

resistance factors for the Canadian [3] and European [17] dead and live load factors exceed the required $\phi = 0.75$ and $\phi = 0.80$, respectively. If the $0.75f_u$ reduction factor is applied to all of the test data the calculated resistance (capacity) factors increase to values far above those factors currently used in the design of bolted connections.

## 5. Conclusions

The results of the bolted connection tests that were completed for this research [10–12] indicate that the current connection provisions set out in the AS/NZS 4600 [1], AISI [2] and Eurocode [17] design standards cannot be used to accurately predict the failure mode of bolted connections that are fabricated from thin G550 and G300 sheet steels. Furthermore, these design standards cannot be used to accurately determine the bearing resistance of bolted specimens based on a failure criterion for predicted loads. It is necessary to incorporate a gradated bearing resistance equation which is dependent on the thickness of the connected material and the bolt diameter, similar to that found in the CSA-S136 design standard [3].

The net section fracture of 0.42 and 0.60 mm, G550 and G300 sheet steels at connections can be accurately and reliably predicted without the use of a stress reduction factor based on the configuration of bolts and specimen width. The net section fracture resistance of a bolted connection that is calculated following the CSA-S136 design standard [3] procedure, where the net cross-sectional area and the ultimate material strength are used, is adequate.

The proposed design method for bolted connections that are loaded in shear can be used to improve the accuracy of the predicted load resistance when thin sheet steels are joined. It is recommended that the gradated bearing coefficient formulation, the unreduced net section resistance, and the Eurocode [17] design method for end pull-out be used in the design of bolted connections.

Calibration of the proposed bolted connection design provisions using the full ultimate strength, $f_u$, and the Australian [34], New Zealand [35] and USA [2] dead and live load factors reveals that the end pull-out and bearing failure equations for the target reliability index are adequate and can be reliably used with $\phi = 0.60$, although higher values could be used based on the test results contained in this paper. Similarly, the use of the proposed equation for net section fracture yields resistance (capacity) factors which exceed the required $\phi = 0.765$ (0.75 USA). Calculated resistance (capacity) factors for the Canadian [3] and European [17] dead and live load factors exceed the required $\phi = 0.75$ and $\phi = 0.80$, respectively, for $\beta_o = 3.5$. The calculated resistance (capacity) factors increase to values far above those factors currently used in the design of bolted connections if the $0.75f_u$ reduction factor is applied to all of the test data.

## Acknowledgements

The authors would like to thank the Australian Research Council and BHP Coated Steel Division for their financial support. The first author is supported by a joint Commonwealth of Australia and Centre for Advanced Structural Engineering Scholarship.

## References

[1] Standards Australia/Standards New Zealand. Cold-formed steel structures—AS/NZS 4600. Sydney, NSW, Australia, 1996.
[2] American Iron and Steel Institute. 1996 Edition of the Specification for the Design of Cold-Formed Steel Structural Members. Washington, DC, USA, 1997.
[3] Canadian Standards Association, S136. Cold Formed Steel Structural Members. Etobicoke, Ont., Canada, 1994.
[4] Dhalla AK, Winter G. Steel ductility measurements. Journal of the Structural Division, ASCE 1974;100(ST2):427–44.
[5] Dhalla AK, Winter G. Suggested steel ductility requirements. Journal of the Structural Division, ASCE 1974;100(ST2):445–62.
[6] Standards Australia. Steel sheet and strip—hot-dipped zinc-coated or aluminium/zinc coated—AS 1397. Sydney, NSW, Australia, 1993.
[7] Rogers CA, Hancock GJ. Ductility of G550 sheet steels in tension—elongation measurements and perforated tests. Research Report No. R735, Centre for Advanced Structural Engineering, University of Sydney, Sydney, NSW, Australia, 1996.
[8] Rogers CA, Hancock GJ. Ductility of G550 sheet steels subjected to tension. Proceedings of the 5th International Colloquium on Stability and Ductility of Steel Structures, Japanese Society of Steel Construction and Nagoya University, Nagoya, Japan, 1997:949–956.
[9] Rogers CA, Hancock GJ. Ductility of G550 sheet steels in tension. Journal of Structural Engineering ASCE 1997;123(12):1586–94.
[10] Rogers CA, Hancock GJ. Bolted connection tests of thin G550 and G300 sheet steels. Research Report No. R749, Centre for Advanced Structural Engineering, University of Sydney, Sydney, NSW, Australia, 1997.
[11] Rogers CA, Hancock GJ. Bolted connection tests of thin G550 and G300 sheet steels. Journal of Structural Engineering, ASCE 1998;124(7):798–808.
[12] Rogers CA, Hancock GJ. New bolted connection design formulae for G550 and G300 sheet steels less than 1.0 mm thick. Research Report No. R769, Centre for Advanced Structural Engineering, University of Sydney, Sydney, NSW, Australia, 1998.
[13] BHP. The Making of Iron and Steel, Seventh Edition, BHP Steel Group, Melbourne Vic, Australia, 1992.
[14] American Society for Testing and Materials A611. Standard Specification for Steel, Sheet, Carbon, Cold-Rolled, Structural Quality, Philadelphia, PA, USA, 1994.
[15] American Society for Testing and Materials A653. Standard Specification for Steel Sheet, Zinc-Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process, Philadelphia, PA, USA, 1994.
[16] American Society for Testing and Materials A792. Standard Specification for Steel Sheet, 55% Aluminum-Zinc Alloy-Coated by the Hot-Dip Process. Philadelphia, PA, USA, 1994.
[17] European Committee for Standardisation, Eurocode 3. Design of steel structures, Part 1.3 General rules, Supplementary rules for cold formed thin gauge members and sheeting. Brussels, Belgium, 1996.
[18] American Iron and Steel Institute. Changes to Specification and Commentary Sections C2, E2, E3.2, E3.3 and E5, Combined LRFD and ASD, Ballot C/S96-66D. Washington, DC, USA, 1998.

[19] Cornell University. Tests on Bolted Connections—Third Progress Report. Unpublished Report for the AISI, 1954.
[20] Cornell University. Tests on Bolted Connections—Fifth Progress Report. Unpublished Report for the AISI, 1954.
[21] Cornell University. Tests on Bolted Connections—Sixth Progress Report. Unpublished Report for the AISI, 1954.
[22] Cornell University. Tests on Bolted Connections—Seventh Progress Report. Unpublished Report for the AISI, 1956.
[23] Winter G. Tests on bolted connections in light gage steel. Journal of the Structural Division, ASCE 1956;82(ST2):920-1–920-25.
[24] Popowich DW. Tension capacity of bolted connections in light gage cold-formed steel. Thesis presented to the Graduate School of Cornell University for the Degree of Master of Science, School of Civil Engineering, 1969.
[25] Rogers CA, Hancock GJ. Failure modes of bolted sheet steel connections loaded in shear. Research Report No. R772, Centre for Advanced Structural Engineering, Department of Civil Engineering, University of Sydney, Sydney, Australia, 1998.
[26] European Convention for Constructional Steelwork, ECCS-TC7. The Design and Testing of Connections in Steel Sheeting and Sections, Publication No. 21, 1983.
[27] American Institute of Steel Construction, Research Council on Structural Connections. Load and Resistance Factor Design—Specification for Structural Joints Using ASTM A325 or A490 Bolts. Chicago, IL, USA, 1988.
[28] American Institute of Steel Construction. Specification for Structural Steel Buildings—Allowable Stress Design and Plastic Design. First Edition, Chicago, IL, USA, 1989.
[29] American Institute of Steel Construction. Load and Resistance Factor Design—Specification for Structural Steel Buildings. Chicago, IL, USA, 1993.
[30] American Society for Testing and Materials A370. Standard Test Methods and Definitions for Mechanical Testing of Steel Products. Philadelphia, PA, USA, 1994.
[31] Zadanfarrokh F, Bryan ER. Testing and Design of Bolted Connections in Cold Formed Steel Sections. Proceedings of the 11th International Speciality Conference on Cold-Formed Steel Structures, University of Missouri-Rolla, Rolla, MO, USA, 1992:625–662.
[32] Bryan ER. The design of bolted joints in cold-formed steel sections. Thin-Walled Structures 1993;16:239–62.
[33] American Iron and Steel Institute. Commentary on the 1996 Edition of the Specification for the Design of Cold-Formed Steel Structural Members. Washington, DC, USA, 1997.
[34] Standards Association of Australia. SAA Loading Code, Part 1: Dead and Live Loads and Load Combinations—AS 1170.1. Sydney, NSW, Australia, 1989.
[35] Standards New Zealand. Code of Practice for General Structural Design and Design Loadings for Buildings—NZS 4203. Wellington, New Zealand, 1992.