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Lip H. Teh[1] and Gregory J. Hancock[2]

Abstract

G450 steel to AS 1397 is a cold-reduced sheet steel with in-line galvanizing. Its grade is 65 ksi (450 MPa) yield and 70 ksi (480 MPa) tensile strength. It is widely used in Australia for purlins, and is being used to fabricate light-weight portal frames, often by welding. The effect of welding on G450 sheet steel in the heat affected zone was unknown and so the project was performed to investigate the strength of fillet welded connections. Transverse and longitudinal fillet welded connections in 0.06 in (1.5 mm) and 0.12 in (3.0 mm) sheet steels were tested to failure. The failure modes and ductility of different types of connections are described. The test results are used to check the design rules in the AISI Specification (Section E2.4) and the Australian/New Zealand Standard for Cold-Formed Steel Structures AS/NZS 4600 (Clause 5.2.3). Recommendations are made for revised capacity factors. The quality of fillet welded connections in thin sheet steels produced by industry fabricators is investigated. The need to complement the macro test with the destructive prying test as part of the pre-qualification procedure for such connections is demonstrated.

Introduction

In Australia and New Zealand, the design rules for cold-formed steel members including connections are specified in AS/NZS 4600 (SA/SNZ 1996a). The design equations for fillet welded connections in thin sheet steels less than 2.5 mm are adapted from the AWS D1.3 Structural Welding Code (AWS 1989), which is based on the laboratory test results of double-lap welded connections in mainly mild sheet steels (Pekoz & McGuire 1980). Since the welds in thin sheet steels are generally as thick as or thicker than the sheets, and the weld metal must be at least as strong as the weaker of the sheets being joined, these equations use the sheet material strength and the sheet thickness (rather than the weld metal strength and the weld throat size) in determining the nominal capacity of the connections. Unfortunately, it is not clear how applicable the equations are to welded connections in high-strength sheet steels manufactured to AS 1397 (SA 1993a). Clause 1.5.1.4 of AS/NZS 4600 states that "The effect of welding on the mechanical properties of a member shall be determined on the basis of tests on the full section containing the weld within the gauge length. Any necessary allowance for such effect shall be made in the structural use of the member." However, no significant research has been conducted on welded connections in cold-reduced high-strength sheet steels such as G450, G500 and G550 steels, which are manufactured to AS 1397. These steels are widely used in Australia for purlin

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and decking applications where welding is often used. Zhao & Hancock (1996) have pointed out that as the tensile strength of the steel is increased by cold working, the heat-affected-zone (HAZ) may play a more important role in the strength of welded connections.

With regard to milder steels including cold-formed tubular sections, it has previously been concluded that welding does not affect the steel properties significantly (Wardenier & Koning 1975a, 1975b). This conclusion supports the existing design equation for the nominal capacity of a transverse fillet welded connection in sheet steel, as specified in Clause 5.2.3.3 of AS/NZS 4600 (SA/SNZ 1996a). It is also consistent with the statement of Pekoz & McGuire (1980) that a butt or transverse fillet welded connection can be expected to develop the full strength of the sheet. However, recent research by Chen et al. (1999) shows that the tensile strength of the heat-affected-zone (HAZ) of G550 sheet steel drops substantially from a nominal value of 80 ksi (550 MPa) to about 65 ksi (450 MPa). This considerable decrease in tensile strength due to welding puts into question the applicability of current design equations to welded connections in cold-reduced high-strength sheet steels such as G450, G500 and G550 sheet steels. Additionally, there is a concern about the effect of reduced ductility especially of G550 steel on the ability of a (long) welded connection to redistribute the stresses prior to fracture in the stress concentration area. It may be noted that with regard to the tensile strength assumed in the design of bolted connections in G550 sheet steel, liberalisation of the design rule which requires that the yield and ultimate strengths be reduced to 75% was recently proposed by Rogers & Hancock (1997).

Thus it is seen that although AS/NZS 4600 (SA/SNZ 1996a) leads the world with the design rules for high-strength steels, there is uncertainty with regard to the design of welded connections in cold-reduced high-strength thin sheet steels. It is the purpose of this paper to provide test data and design guidance for welded connections in G450 sheet steel of various thicknesses manufactured to AS1397 (SA 1993a). The testing program is based on those previously conducted by Pekoz & McGuire (1980) on double-lap connections and by Stark & Soetens (1980) on single-lap connections, which include fillet welds, flare bevel welds, flare vee welds, arc spot welds and arc seam welds. The single-lap connections are included in the program because the formulae proposed by Pekoz & McGuire (1980), which are the basis of the design equations specified in AS/NZS 4600, were found to be unconservative for predicting the strength of single-lap connections (Stark & Soetens 1980). The research results presented by Stark & Soetens (1980) form the basis of the design rules for welded connections in thin sheet steel in Eurocode 3 (CEN 1993).

This paper describes the laboratory tests conducted on fillet welded connections in 0.06-in (1.5-mm) and 0.12-in (3.0-mm) G450 sheet steels, which are cold-reduced high-strength steels having a design yield strength of 65 ksi (450 MPa) and a design tensile strength of 70 ksi (480 MPa). These thicknesses represent the minimum and the maximum thicknesses commonly available, respectively, for G450 sheet steel. The use of these thicknesses ensures that any proposed design rules are applicable to the whole range of thicknesses available to the designer. It may be noted that according to AS/NZS 4600 (SA/SNZ 1996a), in the case of cold-formed tubular sections, a transition point beyond which a fillet welded connection must be designed to AS 4100 (SA 1998) is 0.1 in (2.5 mm). Both transverse and longitudinal loadings (with respect to the welds) are included in the program.

The aim of the testing program is two-fold. Firstly, to verify the reliability of the existing design equations specified in AS/NZS 4600 (SA/SNZ 1996a) for fillet welded connections in G450 sheet steel manufactured to AS 1397 (SA 1993a). Secondly, if necessary, to propose new design equations applicable to fillet welded connections in G450 sheet steel based on the laboratory test results. However, it may be preferred that the existing equations are retained and only the capacity factors are adjusted if feasible.

It is recognised that the quality (or reliability) of the fillet welded connections fabricated in the Civil Engineering Workshop at the University of Sydney, tested and discussed in this paper, may not be matched or even approached by that of similar connections fabricated in the industry at large. For the purpose of gauging the quality of the latter, four industry fabricators chosen at random were asked to replicate the in-house transverse fillet welded connections. These replica connections were tested to failure in order to compare their performance with that of the in-house ones.

The G450 sheet steel materials used in the laboratory tests, which have a trade name GALVASPAN®[3], were manufactured and supplied by BHP Steel Coated Products, Port Kembla. The coating class designation is Z350, which indicates zinc coating of a nominal mass density of 185 g/m2 on each side of the sheet steel (SA 1993a). Tensile loading of all specimens is in the rolling direction of the G450 sheet steel.

Tensile strength of heat-affected-zones (HAZs)

In order to properly assess the ability of the existing design equations to predict the failure loads of fillet welded connections, tests were carried out to determine the approximate tensile strengths of the heat-affected-zones (HAZs) in the G450 sheet steel materials used in the present work. The tensile strengths of the HAZs rather than the measured tensile strengths of the unwelded steels are used in predicting the failure loads of subsequent specimens. This is necessary in order to study the effect of reduced ductility on the strength of longitudinal fillet welded connections, and to enable a more accurate reliability analysis.

Ten 0.06-in sheet specimens and nine 0.12-in sheet specimens were manufactured and tested to failure. These sheet specimens were cut from the same sheets as the subsequent specimens used to verify the reliability of existing design equations. Each specimen was a double-lap transverse fillet welded connection consisting of two hot-rolled steel plates of Grade 450, manufactured to AS/NZS 3678 (SA/SNZ 1996b), abutted together and joined by two G450 sheets as illustrated in Fig. 1. The weld length is the same as the sheet width so that the tensile stresses are assumed to be uniform in the cover sheets. As mentioned previously, the tensile load, which was transverse to the welds, was in the rolling direction of the cover sheets. Each specimen was gripped at the hot-rolled steel plates on both ends, and the distance between the two grips was approximately 15.7 in (400 mm). Such a set-up was also used for subsequent double-lap connection specimens used to verify the reliability of existing design equations.

[3] GALVASPAN® is a registered trademark of BHP Steel (JLA) Pty Ltd.

Although it is not the purpose of the present work to find the optimum welding procedure for G450 sheet steel, two different electrodes and two different shielding gases were used for the specimens. The two electrodes are 0.03-in (0.8-mm) ES6-GC/M-W503AH wire and 0.035-in (0.9-mm) ES4-GC/M-W503AH wire, both of which were manufactured to AS/NZS 2717.1 (SA/SNZ 1996c) and are pre-qualified welding consumables for gas metal-arc welding (GMAW) of G450 sheet steel according to Clause 4.5.1 of AS/NZS 1554.1 (SA/SNZ 1998a). Both shielding gases are argon and carbon-dioxide based, with one containing helium. The settings of the GMAW machine were varied from specimen to specimen while ensuring that acceptable welds were produced. The welding voltage, current and time were recorded using a WeldPrint monitoring machine (Welding Technology Institute 2000).

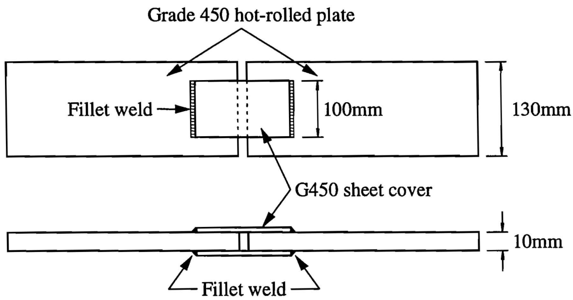

Fig. 1 Diagram of a HAZ specimen

The welding procedure for each HAZ specimen is given in Teh & Hancock (2000). All the specimens failed in the HAZs of the cover sheets rather than in the welds, as illustrated in Fig. 2, so it can be inferred that the weld fusion and penetration of each specimen were satisfactory. Hydrogen cracking was not a concern as G450 sheet steel does not have a sensitive microstructure and the double-lap joints were not highly constrained. The requirements for the chemical composition of G450 sheet steel are specified in AS 1397 (SA 1993a). The electrodes used are hydrogen controlled as denoted by the letter "H" at the end of the classifications.

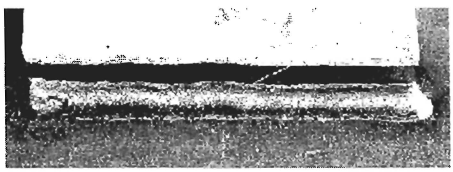

Fig. 2 HAZ failure in 0.12-in G450 sheet steel

The HAZ tensile strength f_{uh} of each specimen is computed from the ultimate test load P_t and the actual dimensions of the cover sheets. The actual dimensions are the average sheet width and the average base metal thickness (with the zinc coating removed). The ultimate test loads listed in Tables 1 and 2 were obtained using a stroke rate of 0.008 in/minute (0.2 mm/minute), which translates to strain rates of the order of 10^{-5} per second for the cover sheets. The average tensile strength of the HAZs in the 0.06-in (1.5-mm) sheet steel was found to be 70.8 ksi (488 MPa), and that in the 0.12-in (3.0-mm) sheet steel was found to be 71.8 ksi (495 MPa).

Table 1 Strength of HAZs in 0.06-in (1.5-mm) G450 sheet steel

	Arc energy		f_{uh}		f_{uh}/f_{un}
	ft-kip/in	kJ/mm	ksi	MPa	
HAZ15.1	4.50	0.24	71.4	492	1.03
HAZ15.2	5.43	0.29	69.9	482	1.00
HAZ15.3	5.25	0.28	69.9	482	1.00
HAZ15.4	5.06	0.27	70.3	485	1.01
HAZ15.5	4.68	0.25	70.6	487	1.01
HAZ15.6	5.43	0.29	70.8	488	1.02
HAZ15.7	5.06	0.27	70.5	486	1.01
HAZ15.8	8.06	0.43	70.1	483	1.01
HAZ15.9	8.06	0.43	71.2	491	1.02
HAZ15.10	5.62	0.30	73.5	507	1.06

Table 2 Strength of HAZs in 0.12-in (3.0-mm) G450 sheet steel

	Arc energy		f_{uh}		f_{uh}/f_{un}
	ft-kip/in	kJ/mm	ksi	MPa	
HAZ30.1	8.62	0.46	73.0	503	1.05
HAZ30.2	9.93	0.53	68.5	472	0.98
HAZ30.3	10.30	0.55	67.6	466	0.97
HAZ30.4	9.74	0.52	71.9	496	1.03
HAZ30.5	8.99	0.48	72.8	502	1.05
HAZ30.6	8.99	0.48	72.2	498	1.04
HAZ30.7	11.80	0.63	71.9	496	1.03
HAZ30.8	11.80	0.63	74.5	514	1.07
HAZ30.9	12.18	0.65	73.7	508	1.06

The last columns of Tables 1 and 2 show the ratios of the measured HAZ tensile strengths f_{uh} to the nominal design tensile strength f_{un} of 70 ksi (480 MPa) specified in AS/NZS 4600 (SA/SNZ

1996a) for G450 sheet steel. It is evident that irrespective of the arc energy and the welding procedures, the tensile strengths of the HAZs do not differ significantly from the nominal tensile strength, although they are significantly lower than the actual tensile strengths of the corresponding coupons cut from the same sheets. The average tensile strength of the 0.06-in G450 sheet steel in the rolling direction was found to be 86.4 ksi (596 MPa), and that of the 0.12-in G450 sheet steel was found to be 76.7 ksi (529 MPa).

In this paper, the average HAZ strengths of 70.8 ksi (488 MPa) and 71.8 ksi (495 MPa) computed from Tables 1 and 2 are used to predict the failure loads of the following double-lap as well as single-lap fillet welded connections in 0.06-in (1.5-mm) and 0.12-in (3.0-mm) G450 sheet steels, respectively. More research is required to correlate the tensile strengths of HAZs in G450 sheet steel to the tensile strength of the virgin steel and the welding procedures used to produce the fillet welds. It is also noted that while the average virgin strength of the 0.06-in sheet steel is higher than that of the 0.12-in sheet steel, the reverse is true with regard to their average HAZ strengths.

In addition to the tension tests described previously, similar tests were also conducted using hot-rolled steel plates of different thicknesses. The purpose is to ascertain that the HAZ strengths of G450 sheet steels welded with different heat inputs do not vary considerably from those reported in Tables 1 and 2. However, only 0.06-in G450 sheet steel was tested as it was believed to be more susceptible to variation in the thickness of the hot-rolled steel plates (and hence the variation in the heat input absorbed by the sheet steel). The test results shown in Table 3 support the previous indication that the HAZ tensile strengths do not differ significantly from the nominal tensile strength of 70 ksi (480 MPa). This is coincidental but seems to be typical of G450 sheet steel manufactured to AS 1397 (SA 1993a).

Table 3 Variation in HAZ strengths in 0.06-in G450 sheet steel with heat input

Plate thickness (in / mm)	Arc energy		f_{uh}		f_{uh}/f_{un}
	ft-kip/in	kJ/mm	ksi	MPa	
0.24 / 6	5.99	0.32	72.4	499	1.04
0.47 / 16	7.12	0.38	72.4	499	1.04
0.79 / 20	5.43	0.29	69.2	477	0.99

It is also evident from all the tables that there is no consistent correlation between the HAZ strength and the amount of welding heat input.

Double-lap transverse fillet welded connections

The specimens used to verify the reliability of Clause 5.2.3.3 of AS/NZS 4600 (SA/SNZ 1996a), or Section E2.4(b) of AISI Specification (AISI 1996), rewritten here as

$$V_w = l_w t f_u \tag{1}$$

for predicting the nominal capacity V_w of a weld of length l_w in a double-lap transverse fillet welded connection in G450 sheet steel of average base thickness t are similar to those used to investigate the HAZ strength in the preceding section. However, for the purpose of studying the potential effect of connection geometry (non-uniform stress distribution), the nominal weld lengths of the specimens were varied from 1.6 in (40 mm) to 4.7 in (120 mm). The welds were situated concentrically with respect to the cover sheets, which are 5.1 in (130 mm) wide rather than 3.9 in (100 mm) as for the previous HAZ specimens illustrated in Fig. 1. The 0.06-in and the 0.12-in sheet specimens were produced using the same weld settings as those used for the HAZ15.1 and HAZ30.1 specimens, respectively. The average base metal thickness of the 0.06-in sheet used for the specimens in this section is 1.51 mm, and that of the 0.12-in sheet is 2.97 mm.

The ratios of the ultimate test loads P_t of the double-lap transverse fillet welded connections to the predicted failure loads P_p computed using Equation (1) are shown in Tables 4 and 5 for the 0.06-in and the 0.12-in sheet specimens, respectively. The values of P_p are twice V_w in Equation (1) with f_u equal to the mean values of f_{uh} shown in Tables 1 and 2 for the 0.06-in and the 0.12-in sheet specimens, which are 70.8 ksi (488 MPa) and 71.8 ksi (495 MPa), respectively. As with the HAZ specimens, the ultimate test loads of the present and subsequent specimens were obtained using a stroke rate of 0.008 in/minute (0.2 mm/minute), which results in sheet strain rates of the order of 10^{-5} per second. The tables show that the design equation specified in Clause 5.2.3.3 of AS/NZS 4600 (SA/SNZ 1996a), or Section E2.4(b) of AISI Specification (AISI 1996), is applicable to double-lap fillet welded connections in G450 sheet steel which are loaded in the transverse direction to the welds, as there are very good agreements between the predicted failure loads and the ultimate test loads. Additionally, the connection strengths per unit weld length were found not to vary consistently with the ratios of the weld length to the sheet width, as evident from the last column of each table.

Table 4 Transverse fillet welds (double lap) in 0.06-in G450 sheet steel

	Average length of failed welds		P_t/P_p
	in	**mm**	
TFWD15.1	1.61	41	1.03
TFWD15.2	2.36	60	1.02
TFWD15.3	3.07	78	1.05
TFWD15.4	3.98	101	1.02
TFWD15.5	4.69	119	1.00

Currently, in Australia and North America the relative reliability of structural design rules including the design equations for connections is described in terms of a safety index, commonly denoted β. A larger value of β indicates a greater reliability. One method of computing the safety index β is the First Order Second Moment method (Cornell 1969, Ravindra & Galambos 1978, Ellingwood et al. 1980, Zhao & Hancock 1993). The FOSM method adopted in this paper, which assumes a log-normal distribution for the resistance and the load, is described in Teh & Hancock

(2000). The statistical parameters common to all types of connections tested in this paper are also given in Teh & Hancock (2000).

Table 5 Transverse fillet welds (double lap) in 0.12-in G450 sheet steel

	Average length of failed welds		P_t/P_p
	in	mm	
TFWD30.1	1.61	41	0.99
TFWD30.2	2.48	63	0.99
TFWD30.3	3.23	82	0.93
TFWD30.4	3.94	100	1.01
TFWD30.5	4.72	120	1.02

The statistical parameters required for the computation of the safety indices for the double-lap transverse fillet welded connections are given in Table 6 and Appendix I, where the statistical parameters common to all types of connections discussed in this paper are grouped together. It was found that the safety indices β for the double-lap transverse fillet welded connections in 0.06-in G450 sheet steel vary between 3.7 and 7.5, while those in 0.12-in G450 sheet steel vary between 3.6 and 7.0. All these values are greater than the target index of 3.5 recommended for connections (SA/SNZ 1998c).

Table 6 Statistical parameters of double-lap transverse fillet welded connections

	0.06-in	0.12-in
P_m	1.02	0.99
V_P	0.02	0.03
R_m/R_n	1.03	1.01
V_R	0.04	0.05
ϕ	0.6	0.6

P_m = mean value of P_t/P_p

V_P = coefficient of variation of P_t/P_p

R_m/R_n = mean ratio of measured resistance to nominal resistance

V_R = coefficient of variation of the ratio of measured resistance to nominal resistance

Based on the testing results and the reliability analysis results, it can be concluded that the design equation specified in Clause 5.2.3.3 of AS/NZS 4600 (SA/SNZ 1996a), or Section E2.4(b) of AISI Specification (AISI 1996), which adopts a capacity factor of 0.6, may be conservatively used to design double-lap fillet welded connections in G450 sheet steel which are loaded in the transverse direction to the welds. This conclusion is valid for such connections in G450 sheet steel of any thickness since the full range of thicknesses was covered in the tests.

Double-lap longitudinal fillet welded connections

The specimen configuration for a double-lap longitudinal fillet welded connection is depicted in Fig. 3. It may be noted that preliminary tests had indicated that the distance of a longitudinal fillet weld from the edge of the cover sheet, which is set to be 20 mm for the specimens as shown in the figure, has no effect on the strength of the connection.

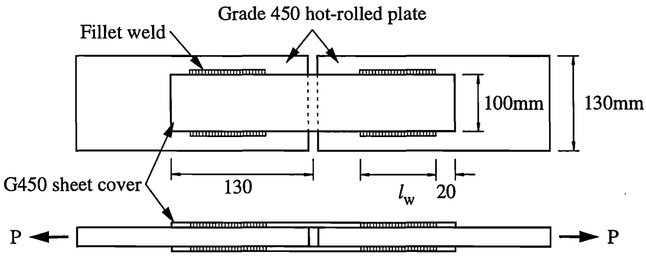

Fig. 3 Diagram of a double-lap longitudinal fillet welded connection specimen

The nominal capacity V_w of each weld in a longitudinal fillet welded connection is specified in Clause 5.2.3.2 of AS/NZS 4600 (SA/SNZ 1996a), or Section E2.4(a) of AISI Specification (AISI 1996) rewritten here as

$$V_w = (1 - 0.01 l_w / t) l_w t f_u \text{ ; } \phi = 0.60 \quad \text{for } l_w/t < 25 \tag{2a}$$

$$V_w = 0.75 l_w t f_u \text{ ; } \phi = 0.55 \quad \text{for } l_w/t \geq 25 \tag{2b}$$

Equation (2a) is intended to account for the effect of geometry which results in decreasing connection strength per unit length with increasing weld length. Since the average base metal thickness of the 0.06-in sheet steel used for the present specimens is 1.53 mm (0.06 in), and that of the 0.12-in sheet steel is 2.97 mm (0117 in), Equation (2a) only applies to 0.06-in sheet specimens with welds no longer than 1.5 in (38 mm), and to 0.12-in specimens with welds no longer than 2.9 in (74 mm).

The ratios of the ultimate test loads P_t of the double-lap longitudinal fillet welded connections to the predicted failure loads P_p computed using Equation (2) are shown in Tables 7 and 8 for the 0.06-in and the 0.12-in sheet specimens, respectively. It is evident from the tables that the design equations specified in Clause 5.2.3.2 of AS/NZS 4600 (SA/SNZ 1996a) significantly overestimate the failure load of a double-lap fillet welded connection in G450 sheet steel which is loaded in the longitudinal direction of the welds. It appears that the current design equations do not adequately account for the effect of geometry on a longitudinal fillet welded connection (i.e. the highly non-uniform stress distribution around the weld) in G450 sheet steel. The relative lack of ductility of the cold-reduced high-strength G450 sheet steel compared to mild steels means that such a connection in G450 sheet steel has a more limited scope to redistribute the stresses away from the stress concentration area, leading to earlier failure.

Table 7 Longitudinal fillet welds (double lap) in 0.06-in G450 sheet steel

	Average length of failed welds		P_t/P_p
	in	**mm**	
LFWD15.1	1.30	33	0.95
LFWD15.2	1.97	50	0.85
LFWD15.3	2.44	62	0.86
LFWD15.4	3.11	79	0.81
LFWD15.5	3.58	91	0.81

Table 8 Longitudinal fillet welds (double lap) in 0.12-in G450 sheet steel

	Average length of failed welds		P_t/P_p
	in	**mm**	
LFWD30.1	1.65	42	0.84
LFWD30.2	2.05	52	0.82
LFWD30.3	2.40	61	0.84
LFWD30.4	2.91	74	0.87
LFWD30.5	3.27	83	0.84

The statistical parameters required for the computation of the safety indices of the double-lap longitudinal fillet welded connections are given in Table 9 and Appendix I. It was found that the safety indices β for the double-lap longitudinal fillet welded connections in both the 0.06-in and the 0.12-in G450 sheet steels vary between 3.0 and 5.8. These values are significantly higher than the target index of 2.5 recommended for cold-formed steel members (SA/SNZ 1998c), but some of the indices are below the target index of 3.5 recommended for connections.

Table 9 Statistical parameters of double-lap longitudinal fillet welded connections

	0.06-in	**0.12-in**
P_m	0.86	0.84
V_P	0.06	0.02
R_m/R_n	0.86	0.86
V_R	0.07	0.04
ϕ	0.60/0.55	0.60/0.55

P_m = mean value of P_t/P_p

V_P = coefficient of variation of P_t/P_p

R_m/R_n = mean ratio of measured resistance to nominal resistance

V_R = coefficient of variation of the ratio of measured resistance to nominal resistance

Traditionally, the target index recommended for connections is set higher than that recommended for members to ensure the failure of a structure is not initiated in the connections (SA/SNZ 1998c). In many cases, connection failures are more brittle than member failures, and give little warning prior to their occurrence. However, this may not always be the case. Figure 4 shows that a longitudinal fillet welded connection exhibits a much more ductile behaviour compared to a transverse fillet welded connection, an example of which is plotted in Fig. 5. It should be noted that a butt welded connection in G450 sheet steel, of which failure is classified as a member rather than connection failure, behaves in a less ductile manner similar to that of a transverse fillet welded connection. Therefore, it can be argued that the target safety index for a longitudinal fillet welded connection should not be higher than that for a butt welded connection, which is 2.5. If this argument is accepted, then Clause 5.2.3.2 of AS/NZS 4600 (SA/SNZ 1996a) may be used to design a double-lap longitudinal fillet welded connection. However, a higher and uniform capacity factor of 0.65 can still be used to achieve the target index of 2.5.

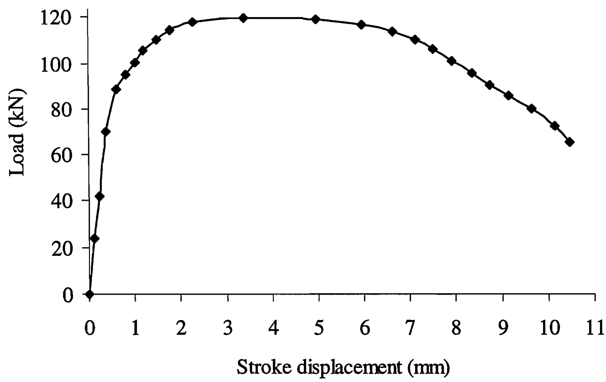

Fig. 4 Load-deflection graph of specimen LFWD15.3

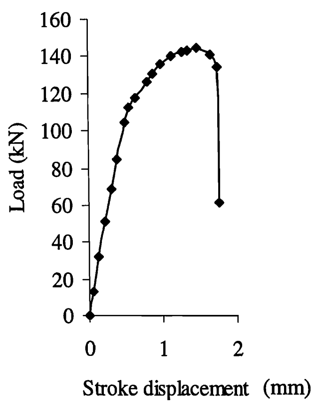

Fig. 5 Load-deflection graph of specimen HAZ15.6

Alternatively, using a uniform capacity factor of 0.55 for Equations (2a) and (2b) results in safety indices which vary between 3.3 and 5.8 for the 0.06-in (1.5-mm) sheet specimens, and between 3.4 and 6.5 for the 0.12-in (3.0-mm) specimens. For most loading combinations, the safety indices β are greater than the target index of 3.5, as plotted in Fig. 6. The variable D_n denotes the nominal dead load, and the variable L_n denotes the nominal live load. Thus the lower bound values correspond to the case of live load only.

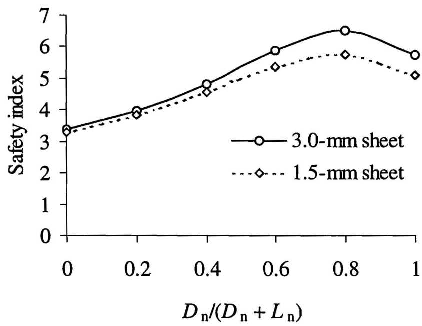

Fig. 6 Safety indices of LFWDs assuming a uniform capacity factor of 0.55

It is of interest to note that although the mean ratios of ultimate test loads P_t to predicted failure loads P_p of the double-lap longitudinal fillet welded connections are roughly the same for the 0.06-in and the 0.12-in sheet specimens, the failure modes may depend on the sheet thickness. The longitudinal fillet welded connections in the 0.06-in sheet steel fail in the HAZs as shown in Fig. 7, while those in the 0.12-in sheet steel fail mostly in the welds as shown in Fig. 8.

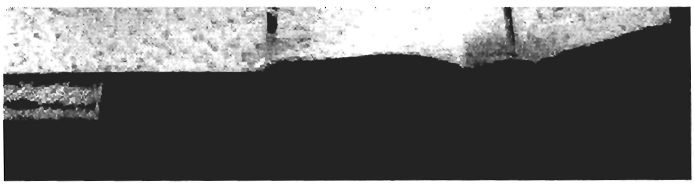

Fig. 7 HAZ failure of double-lap longitudinal fillet welded connection in 0.06-in sheet steel

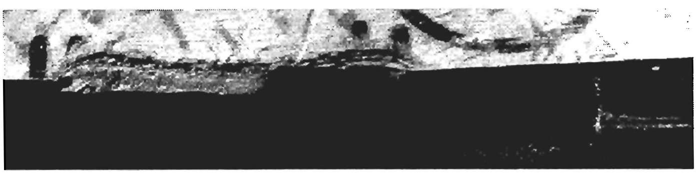

Fig. 8 Weld failure of double-lap longitudinal fillet welded connection in 0.12-in sheet steel

The difference in failure modes is apparently due to the fact that the fillet welds in the thinner 0.06-in cover sheets were invariably larger than the sheet thickness, while those in the thicker 0.12-in cover sheets were not necessarily so particularly near the ends of each weld. For a double-lap longitudinal fillet welded connection, as the tension load increases, the cover sheet is subjected to peeling action which tends to tear up each weld from one end. As the welds "tapered" at the start and at the end of welding, the peeling action resulted in tearing of the welds in the 0.12-in sheet as depicted in Fig. 8. However, weld tearing only occurred after the ultimate load was passed. This phenomenon may explain the similarity in the ratios of ultimate test loads to predicted failure loads between the 0.06-in and the 0.12-in sheet specimens.

Single-lap transverse fillet welded connections

The configuration of the single-lap transverse fillet welded connections tested in the present work is depicted in Fig. 9. The welding procedures for the sheet-to-sheet transverse fillet welds are given in Teh & Hancock (2000). Two different electrodes 0.03-in (0.8-mm) ES6-GC/M-W503AH and 0.035-in (0.9-mm) ES4-GC/M-W503AH) were used for the single-lap connections in 0.06-in sheet steel. For the single-lap connections in 0.12-in sheet steel, only the 0.8-mm wire was used as the 0.9-mm wire resulted in unsatisfactory welds. All the specimens failed in the HAZs rather than in the welds as illustrated in Figs. 10 and 11 for the 0.06-in and the 0.12-in specimens, respectively.

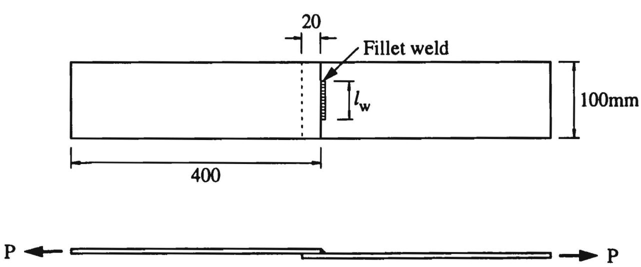

Fig. 9 Diagram of a single-lap transverse fillet welded connection specimen

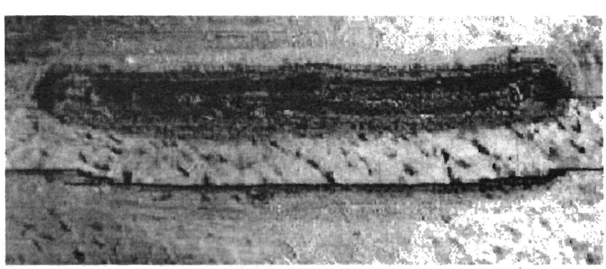

Fig. 10 HAZ failure of a single-lap transverse fillet welded connection in 0.06-in sheet steel

Fig. 11 HAZ failure of a single-lap transverse fillet welded connection in 0.12-in sheet steel

The predicted failure loads P_p of the single-lap transverse fillet welded connections were computed using Equation (1). The average base metal thickness of the 0.06-in sheet steel used for the present specimens is 1.49 mm (0.059 in), and that of the 0.12-in sheet steel is 2.97 mm (0.117 in). Tables 10 and 11 show that unlike the double-lap connections, the failure load of a single-lap transverse fillet welded connection in G450 sheet steel is unconservatively predicted by Equation (1). This is apparently due to the fact that the single-lap connections are subjected to "inclination failure" (Stark & Soetens 1980) as illustrated in Fig. 12 (the specimen shown in the figure is from a preliminary test). It also appears from the ratios P_t / P_p shown in Table 11 that, for a single-lap connection in 0.12-in sheet steel with a transverse fillet weld shorter than 1.6 in (40 mm), the inclination has insignificant effects.

Table 10 Transverse fillet welds (single-lap) in 0.06-in G450 sheet steel

	Actual length of weld		P_t/P_p	P_t /TNO
	in	mm		
TFWS15.1	1.22	31	0.80	0.88
TFWS15.2	1.81	46	0.75	0.87
TFWS15.3	2.36	60	0.84	1.02
TFWS15.4	2.95	75	0.86	1.11
TFWS15.5	3.54	90	0.80	1.10
TFWS15.6	1.30	33	0.96	1.06
TFWS15.7	1.77	45	0.84	0.97
TFWS15.8	2.52	64	0.90	1.12
TFWS15.9	3.07	78	0.87	1.14
TFWS15.10	3.62	92	0.90	1.25

Table 11 Transverse fillet welds (single-lap) in 0.12-in G450 sheet steel

	Actual length of weld		P_t/P_p	P_t /TNO
	in	mm		
TFWS30.1	1.26	32	1.03	1.14
TFWS30.2	1.61	41	1.01	1.15
TFWS30.3	2.48	63	0.91	1.12
TFWS30.4	2.76	70	0.87	1.10
TFWS30.5	3.54	90	0.87	1.19

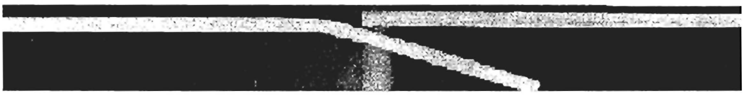

Fig. 12 Inclination of a single-lap transverse fillet welded connection in 0.12-in sheet

It can be seen from the last columns of Tables 10 and 11 that the TNO equation proposed by Stark & Soetens (1980)

$$V_w = \left(1 - 0.3\frac{l_w}{b}\right) l_w t f_u \tag{3}$$

in which b is the sheet width, tends to underestimate the failure load of a single-lap transverse fillet welded connection, particularly ones with relatively long welds. It can also be seen from the ratios of the ultimate test loads P_t to the predicted failure loads P_p, the latter of which were computed using Equation (1), that there is no consistent decrease in the connection strength per unit weld length as the weld length increases when inclination failure prevails.

The statistical parameters required for the computation of the safety indices of the single-lap transverse fillet welded connections are given in Table 12 and Appendix I. It was found that the safety indices β for the connections in 0.06-in G450 sheet steel vary between 2.9 and 4.9, while those in 0.12-in G450 sheet steel vary between 3.3 and 5.4. These values are higher than the target index of 2.5 recommended for cold-formed steel members (SA/SNZ 1998c), but some of the indices are well below the target index of 3.5 recommended for connections. Using a capacity factor of 0.55 results in safety indices which vary between 3.3 and 5.8 for the 0.06-in sheet connections, and between 3.6 and 6.1 for the 0.12-in sheet connections.

Table 12 Statistical parameters of single-lap transverse fillet welded connections

	0.06-in	0.12-in
P_m	0.85	0.94
V_P	0.06	0.08
R_m/R_n	0.86	0.96
V_R	0.07	0.09
ϕ	0.6	0.6

P_m = mean value of P_t/P_p

V_P = coefficient of variation of P_t/P_p

R_m/R_n = mean ratio of measured resistance to nominal resistance

V_R = coefficient of variation of the ratio of measured resistance to nominal resistance

Single-lap longitudinal fillet welded connections

The configuration of the single-lap longitudinal fillet welded connections is depicted in Fig. 13. As for the single-lap transverse fillet welded connections in 0.06-in sheet, two electrodes were used for the connections in the 0.06-in sheet steel. The welding procedures for the single-lap longitudinal fillet welds in 0.06-in sheet steel using 0.03-in (0.8-mm) ES6-GC/M-W503AH and 0.035-in (0.9-mm) ES4-GC/M-W503AH electrodes are given in Teh & Hancock (2000). The single-lap connections in the 0.12-in sheet steel used 0.8-mm wire only.

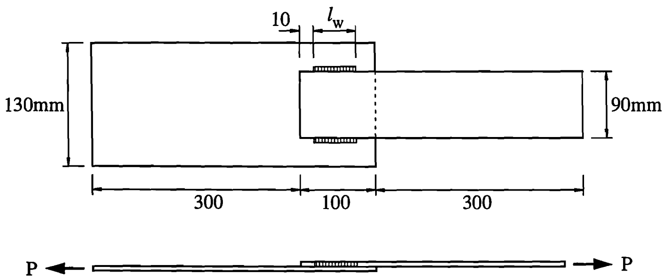

Fig. 13 Diagram of a single-lap longitudinal fillet welded connection specimen

As with the double-lap longitudinal fillet welded connections, the 0.06-in sheet specimens failed in the HAZs (see Fig. 14) while the 0.12-in specimens failed in the welds (see Fig. 15). However, unlike the double-lap connections, weld tearing in the 0.12-in single-lap connections started from both ends of each weld as evident in Fig. 15. This is because both ends of the weld were subjected to peeling action.

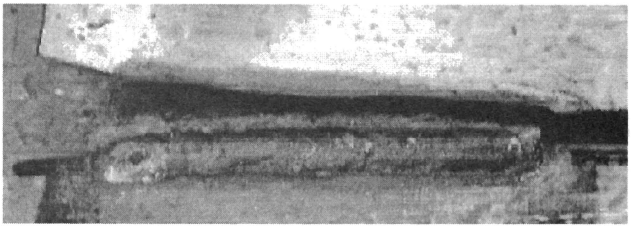

Fig. 14 HAZ failure of a single-lap longitudinal fillet welded connection in 0.06-in sheet steel

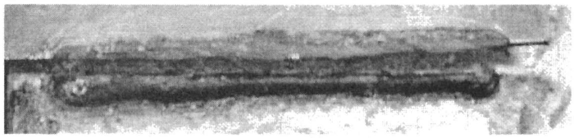

Fig. 15 Weld failure of a single-lap longitudinal fillet welded connection in 0.12-in sheet

Again, despite the difference in failure mode between the 0.06-in and the 0.12-in sheet specimens, the ratios of ultimate test loads P_t to predicted failure loads P_p computed using Equation (2) shown in Tables 13 and 14 suggest that one design equation can be used for single-lap longitudinal fillet welded connections in the whole range of sheet thicknesses between 0.06 in (1.5 mm) and 0.12 in (3.0 mm). This convenience is due to the fact that the ultimate loads of the 0.12-in sheet specimens were reached prior to weld tearing, which means that the failure loads of the longitudinal fillet welded connections in the 0.06-in and in the 0.12-in sheets were controlled by the same factors.

Comparisons of the ratios P_t/P_p shown in Tables 7, 8, 13 and 14 suggest that for the sake of simplicity, double-lap and single-lap longitudinal fillet welded connections may be designed with one common equation. This is in contrast to the transverse fillet welded connections where the single-lap connections are significantly weaker due to inclination failure (see Fig. 12).

The last columns of Tables 13 and 14 list the ratio of the ultimate test load to the predicted failure load of each specimen computed using the TNO equation (Stark & Soetens 1980)

$$V_w = \left(0.95 - 0.45\frac{l_w}{b}\right) l_w t f_u \qquad (4)$$

in which b is the width of the narrower sheet. It can be seen that Equation (4) overestimates the failure loads of single-lap longitudinal fillet welded connections with short welds but underestimates those with longer welds. In fact, the ratios of ultimate test loads P_t to predicted failure loads P_p, the latter computed using Equation (2b) for all the single-lap connections in 0.06-in sheet steel, indicate that there is no consistent deterioration in connection strength per unit length with increasing weld length.

Table 13 Longitudinal fillet welds (single-lap) in 0.06-in G450 sheet steel

	Average length of welds		P_t/P_p	P_t /TNO
	in	mm		
LFWS15.1	1.65	42	0.78	0.79
LFWS15.2	2.05	52	0.81	0.88
LFWS15.3	2.36	60	0.74	0.85
LFWS15.4	2.80	71	0.76	0.96
LFWS15.5	3.23	82	0.75	1.04
LFWS15.6	2.09	53	0.80	0.88
LFWS15.7	2.44	62	0.79	0.92
LFWS15.8	2.76	70	0.81	1.01
LFWS15.9	3.11	79	0.76	1.02

Table 14 Longitudinal fillet welds (single-lap) in 0.12-in G450 sheet steel

	Average length of welds		P_t/P_p	P_t /TNO
	in	mm		
LFWS30.1	1.65	42	0.76	0.88
LFWS30.2	2.05	52	0.78	0.93
LFWS30.3	2.48	63	0.78	0.97
LFWS30.4	2.83	72	0.81	1.04
LFWS30.5	3.23	82	0.76	1.06

The statistical parameters required for the computation of the safety indices of the single-lap longitudinal fillet welded connections are given in Table 15 and Appendix I. For the 0.12-in specimens, two capacity factors are used as per Equations (2a) and (2b). It was found that the safety indices β for the connections in 0.06-in G450 sheet steel vary between 3.0 and 5.5, while those in 0.12-in G450 sheet steel vary between 2.7 and 5.0. These values are higher than the target index of 2.5 recommended for cold-formed steel members (SA/SNZ 1998c), but some of the indices are well below the target index of 3.5 recommended for connections. Using the same argument as for the double-lap longitudinal fillet welded connections, it is suggested that Clause 5.2.3.2 of AS/NZS 4600 may be used to design single-lap longitudinal fillet welded connections. Figure 16 demonstrates the ductile behaviour of specimen LFWS15.7. It should also be noted that substantial "out-of-plane" deformations took place in all specimens prior to reaching the ultimate loads, providing warning that failure of such a connection is imminent. Alternatively, using a uniform capacity factor of 0.50 results in safety indices which vary between 3.4 and 6.4 for the 0.06-in specimens, and between 3.4 and 6.7 for the 0.12-in specimens.

Table 15. Statistical parameters of single-lap longitudinal fillet welded connections

	0.06-in	**0.12-in**
P_m	0.78	0.78
V_P	0.03	0.02
R_m/R_n	0.78	0.80
V_R	0.04	0.04
ϕ	0.55	0.60/0.55

P_m = mean value of P_t/P_p

V_P = coefficient of variation of P_t/P_p

R_m/R_n = mean ratio of measured resistance to nominal resistance

V_R = coefficient of variation of the ratio of measured resistance to nominal resistance

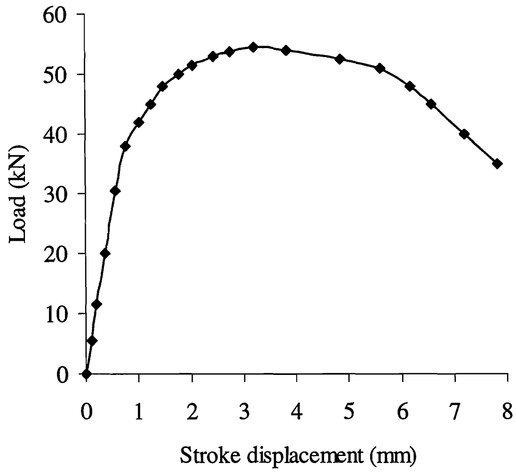

Fig. 16 Load-deflection graph of LFWS15.7

Fabricators' specimens and macro test

Four industry fabricators were selected at random and were asked to reproduce the transverse fillet welded connections in 0.06-in and 0.12-in G450 sheet steels. The configuration of these specimens is shown in Fig. 1. Each fabricator, who claimed to be able to "do the job", was given the materials for practice so that they could determine the "appropriate" welding settings for each type of connection. No instructions were given as to the type of electrodes or shielding gases that should be used in the fabrication. The welding consumables and some welding parameters used by the fabricators are given in Teh & Hancock (2001).

For each type of connection, only one specimen was produced by each industry fabricator. The specimens from the industry fabricators were then tested in the same manner as the specimens reported by the authors. Table 16 lists the ratios of the ultimate test loads to the nominal failure loads of the fabricators' specimens, the latter computed using the nominal tensile strength of 70 ksi (480 MPa) specified in AS/NZS 4600 (SA/SNZ 1996a). For the purpose of comparison, the average ratios of the in-house specimens reported in Tables 1 and 2 are also included in the table. The connection designations used in Table 16 are consistent with those used in Tables 4 and 5.

Table 16 Test results of fabricators' specimens (P_t/P_p)

Fabricator	TFWD15	TFWD30
In-house*	1.04	1.02
A	1.07	0.98
B	0.91	0.95
C	1.01	0.54
D	0.30	0.84

*Average values of specimens tested

It is evident from Table 16 that only Fabricator A produced fillet welded connections comparable to the in-house ones. However, the transverse fillet welded connection in 0.12-in sheet steel (TFWD30) produced by this fabricator failed in the weld as shown in Fig. 17.

Fig. 17 Fracture of transverse fillet weld in 0.12-in sheet steel produced by Fabricator A

Although the transverse fillet welded connection in 0.12-in sheet steel (TFWD30) produced by Fabricator B has a ratio P_t/P_p of 0.95, the welds are grossly oversized as shown in Fig. 18. Such a fillet weld may not be acceptable in practice because of its excessive size.

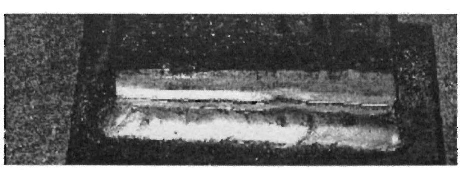

Fig. 18 Fillet weld in 0.12-in sheet steel produced by Fabricator B

The transverse fillet welded connection in 0.12-in sheet steel (TFWD30) produced by Fabricator C failed at half the expected ultimate load. This was due to the lack of fusion as evident from Fig. 19, which shows the cross-section cut from the intact fillet weld. Only the upper half of the sheet steel had been welded, and this flaw could not be revealed from visual inspection of the completed fillet weld. This finding supports the requirement of Clause 4.7.1 of AS/NZS 1554.1 (SA/SNZ 2000) that pre-qualified SP fillet welds be subjected to macro test.

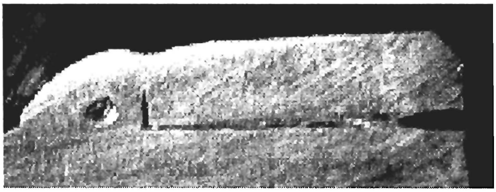

Fig. 19 Lack of fusion in Fabricator C's fillet weld

Worst of all, the transverse fillet welded connection in 0.06-in sheet steel (TFWD15) produced by Fabricator D failed at one third of the expected ultimate load. A macro examination of the intact fillet weld did not reveal any flaws, but visual inspection of the sheet steel where the fillet weld had failed showed that there is uneven weld fusion along the weld as shown in Fig. 20. This is also the explanation for the relatively low ultimate test load of the fillet welded connection in 0.12-in sheet steel produced by the same fabricator. This result indicates that macro test as a pre-qualification procedure for fillet welds in thin sheet steels should be complemented with the destructive prying test illustrated in Fig. 21, as required by the AWS D1.3 Structural Welding Code (AWS 1989).

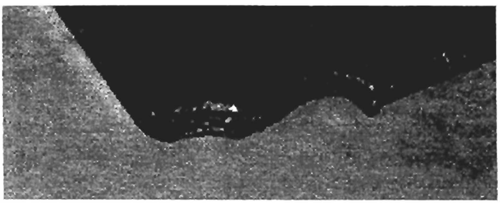

Fig. 20 Uneven fillet weld fusion

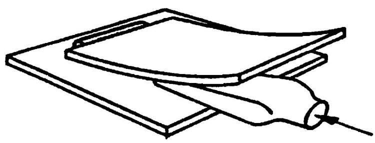

Fig. 21 Destructive prying test of fillet weld in thin sheet steel

Conclusions

Double-lap fillet welded connections composed of G450 sheet steels manufactured to AS 1397 and hot-rolled plates of Grade 450 manufactured to AS 3678 have been produced and tested in the transverse and the longitudinal directions of the welds. Single-lap fillet welded connections in G450 sheet steels have also been produced and tested in the same manner as the double-lap connections. Welding procedures which resulted in satisfactory fillet welds for both types of connections were achieved.

Based on the laboratory test results of the in-house fabricated specimens and the reliability analyses using the FOSM method, the following conclusions, which cover the full range of G450 sheet steel thicknesses between 0.6 in (1.5 mm) and 0.12 in (3.0 mm), can be made:

- The tensile strength of the heat-affected-zone (HAZ) in G450 sheet steel is significantly lower than that of the virgin steel, but is generally higher than the nominal tensile strength of 70 ksi (480 MPa).
- Transverse fillet welded connections which do not undergo inclination failure can be reliably designed using the equation specified in Clause 5.2.3.3 of AS/NZS 4600, or Section E.2.4(b) of AISI Specification, with the existing capacity factor of 0.6, resulting in safety indices greater than 3.5.
- Transverse fillet welded connections which undergo inclination failure and which are designed using the equation specified in Clause 5.2.3.3 of AS/NZS 4600, or Section E.2.4(b) of AISI Specification, with a capacity factor of 0.6, have safety indices significantly greater than 2.5. They can be designed with a reduced capacity factor of 0.55 to give safety indices of at least 3.3. For most loading combinations, the safety index is greater than 3.5.
- Single-lap and double-lap longitudinal fillet welded connections can be designed using the equation specified in Clause 5.2.3.2 of AS/NZS 4600, or Section E.2.4(a) of AISI Specification, with the existing capacity factors of 0.6 and 0.55 as applicable, resulting in safety indices greater than 2.5. The target safety index for longitudinal fillet welded connections should arguably not be greater than that for butt welded connections, which is 2.5, as the former behave in a much more ductile manner. For double-lap longitudinal fillet welded connections, the use of a uniform capacity factor of 0.55 results in safety indices that are greater than 3.5 for most loading combinations.

In general, the connection strengths per weld length were found not to vary consistently with the ratio of the weld length to the sheet width or the sheet thickness. However, the reduced ductility of G450 sheet steel compared to mild steels leads to significantly lower failure loads of the longitudinal fillet welded connections. Single-lap transverse fillet welded connections with relatively long welds are subjected to inclination failure which lowers the connection capacity.

There is a concern regarding the quality of fillet welded connections in thin sheet steels fabricated in the industry at large. Of the four industry fabricators sampled at random, none was able to achieve the quality of the in-house specimens that ensure that failure always occurs in the sheet steel instead of the fillet weld. It was found that the macro test should be complemented by the destructive prying test as part of the pre-qualification procedure of SP fillet welds in thin sheet steels.

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Appendix I – Statistical parameters common to all types of connections

The statistical parameters assumed to be common to all types of connections discussed in this paper are the mean ratio of actual material strength to nominal material strength M_m, the corresponding coefficient of variation V_m, the mean ratio of actual geometric property to nominal geometric property F_m, the corresponding coefficient of variation V_F, the dead load factor γ_D, the coefficient of variation in the dead load V_D, the live load factor γ_L, the coefficient of variation in the live load V_L, the mean ratio of actual dead load to nominal dead load D_m/D_n, and the mean ratio of actual live load to nominal live load L_m/L_n. The values of these parameters as used in the present reliability analyses are given in the following table.

M_m	1.02/1.03
V_M	0.03
F_m	0.99
V_F	0.02
γ_D	1.25
V_D	0.10
γ_L	1.50
V_L	0.25
D_m/D_n	1.05
L_m/L_n	1.00

The values of M_m is assumed to be 1.02 for the 0.06-in (1.5-mm) G450 sheet steel, and 1.03 for the 0.12-in (3.0-mm) steel. Discussions on this parameter and the other parameters shown in the table can be found in Teh & Hancock (2000).

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