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STRENGTH OF FILLET WELDED CONNECTIONS IN G450 SHEET STEELS

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

Abstract

This paper investigates the reliability of the existing design equations specified in AS/NZS 4600:1996 for fillet welded connections in cold-reduced high-strength G450 sheet steels. The existing design equations are adapted from the AWS D1.3 Structural Welding Code, which is based on the testing results of double-lap connections in mainly mild sheet steels. Double-lap and single lap fillet welded connections in 1.5-mm and 3.0-mm sheet steels are manufactured using different GMAW procedures and tested to failure. The approximate tensile strengths of the heat-affected-zones (HAZs), which are significantly lower than the corresponding tensile strengths of the virgin sheet steels, are used to predict the failure loads of the specimens. The HAZ strengths are close to the nominal design tensile strength of 480 MPa specified in AS/NZS 4600:1996. Despite this fortuitous agreement, the lack of ductility of G450 sheet steels compared to mild steels leads to earlier failure of the fillet welded connections loaded in the longitudinal direction of the welds. Failure modes of different types of connections and of connections in different sheet thicknesses are described and discussed. Relaxation of the target safety index for longitudinal fillet welded connections is proposed. It is suggested that the existing design rules may be applied conservatively to transverse fillet welded connections which do not undergo inclination failure, and to longitudinal fillet welded connections.

Keywords: cold-formed steel, design standards, fillet welds, load and resistance factor design, sheet metal, welded connections

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1 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 welded connections in thin sheet steels less than 3.0 mm (2.5 mm for fillet welds) specified in the standard are adapted from the AWS D1.3 Structural Welding Code (AWS 1989), which is based on the testing 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. 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.

It is noteworthy that 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 shows that the tensile strength of the heat-affected-zone (HAZ) of G550 sheet steel drops substantially from a nominal value of 550 MPa to about 450 MPa (Chen et al. 1999). 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 project to provide test data and design guidance for welded connections in G450, G500 and G550 sheet steels 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 (Eurocode 1992).

This paper describes the laboratory tests conducted on fillet welded connections in 1.5-mm and 3.0-mm G450 sheet steels, which are cold-reduced high-strength steels having a design yield strength of 450 MPa and a design tensile strength of 480 MPa (SA/SNZ 1996a). 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 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 2.5 mm (SA/SNZ 1996a). 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 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.

The G450 sheet steel materials used in the laboratory tests, which have a trade name GALVASPAN, 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/m^2 on each side of the sheet steel (SA 1993a). Tensile testing of the specimens was performed using a 2000-kN capacity Dartec servo-controlled testing machine manufactured in Stourbridge, England, and an MTS Teststar digital controller. Tensile loading of all specimens was in the rolling direction of the G450 sheet steel.

2 Tensile strength of 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 HAZs in the G450 sheet steel materials used in the present work. The approximate tensile strengths of the HAZs are used in predicting the failure loads of subsequent specimens. As will be seen later, the average tensile strengths of the HAZs are significantly lower than the corresponding average tensile strengths of the virgin steels, particularly for the 1.5-mm sheet steel.

Ten 1.5-mm sheet specimens and nine 3.0-mm 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 $350 \times 130 \times 10\text{mm}$ hot-rolled steel plates of Grade 450, manufactured to AS/NZS 3678 (SA/SNZ 1996b), abutted together and joined by two $100 \times 100\text{mm}$ 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 400 mm. Such a set-up was also used for subsequent double-lap connection specimens used to verify the reliability of existing design equations.

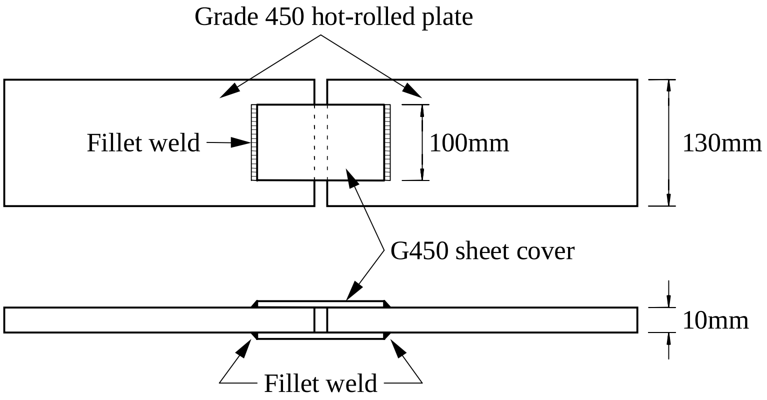

Fig. 1 Diagram of a HAZ specimen

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 0.8-mm ES6-GC/M-W503AH wire and 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 compositions of the gases are given in the welding procedure appendices). 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).

The welding procedure for each HAZ specimen is given in Appendix I. 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 as specified in AS 1397 (SA 1993a) are shown in Appendix II. It may also be noted that both the electrodes used in the welding are hydrogen controlled as denoted by the letter “H” at the end of the classifications.

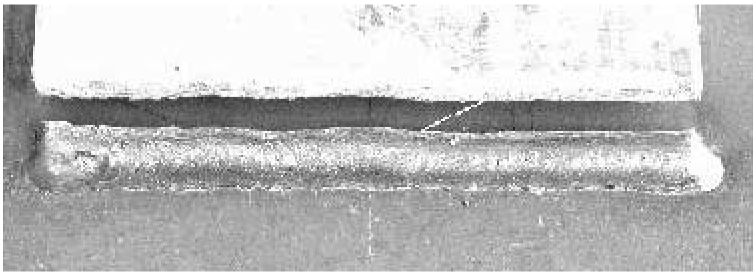

Fig. 2 HAZ failure in 3.0-mm G450 sheet steel

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 0.2 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 1.5-mm sheet steel was found to be 488 MPa, and that in the 3.0-mm sheet steel was found to be 495 MPa.

Table 1. Strength of HAZs in 1.5-mm G450 sheet steel

	Arc energy (kJ/mm)	**Dimensions (mm^2)**	**P_t (kN)**	**f_{uh} (MPa)**	**f_{uh}/f_{un}**
HAZ15.1	0.24	101×1.53	152.0	492	1.03
HAZ15.2	0.29	101×1.53	149.0	482	1.00
HAZ15.3	0.28	101×1.53	149.0	482	1.00
HAZ15.4	0.27	101×1.53	150.0	485	1.01
HAZ15.5	0.25	101×1.53	150.5	487	1.01
HAZ15.6	0.29	100×1.48	144.5	488	1.02
HAZ15.7	0.27	100×1.48	144.0	486	1.01
HAZ15.8	0.43	100×1.48	143.0	483	1.01
HAZ15.9	0.43	100×1.48	145.5	491	1.02
HAZ15.10	0.30	100×1.48	150.0	507	1.06

Table 2. Strength of HAZs in 3.0-mm G450 sheet steel

	Arc energy (kJ/mm)	**Dimensions (mm^2)**	**P_t (kN)**	**f_{uh} (MPa)**	**f_{uh}/f_{un}**
HAZ30.1	0.46	101×2.97	302.0	503	1.05
HAZ30.2	0.53	101×2.97	284.0	472	0.98
HAZ30.3	0.55	101×2.97	280.5	466	0.97
HAZ30.4	0.52	101×2.97	298.0	496	1.03
HAZ30.5	0.48	100×2.97	298.5	502	1.05
HAZ30.6	0.48	100×2.97	296.0	498	1.04
HAZ30.7	0.63	100×2.97	294.5	496	1.03
HAZ30.8	0.63	100×2.97	305.5	514	1.07
HAZ30.9	0.65	100×2.97	302.0	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 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 1.5-mm G450 sheet steel in the rolling direction was found to be 596 MPa, and that of the 3.0-mm G450 sheet steel was found to be 529 MPa. Thus the close agreement between the tensile strengths of the HAZs and the nominal tensile strength of 480 MPa used in the design of fillet welded connections (SA/SNZ 1996a) is fortuitous.

In this paper, the average HAZ strengths of 488 MPa and 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 1.5-mm and 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 1.5-mm sheet steel is higher than that of the 3.0-mm sheet steel, the reverse is true with regard to their average HAZ strengths.

3 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), 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 40 mm to 120 mm. The welds were situated concentrically with respect to the cover sheets, which are 130 mm wide (rather than 100 mm as for the previous HAZ specimens illustrated in Fig. 1). The 1.5-mm and the 3.0-mm 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 1.5-mm sheet used for the specimens in this section is 1.51 mm, and that of the 3.0-mm sheet is 2.97 mm.

The ultimate test load P_t and the predicted failure load P_p of each double-lap transverse fillet welded connection computed using Equation (1) are shown in Tables 3 and 4 for the 1.5-mm and the 3.0-mm 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 1.5-mm and the 3.0-mm sheet specimens, which are 488 MPa and 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 0.2 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) 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 3. Transverse fillet welds (double lap) in 1.5-mm G450 sheet steel

	Average length of failed welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**
TFWD15.1	41	62.5	60.4	1.03
TFWD15.2	60	90.0	88.4	1.02
TFWD15.3	78	120.5	115.0	1.05
TFWD15.4	101	151.5	148.8	1.02
TFWD15.5	119	175.0	175.4	1.00

Table 4. Transverse fillet welds (double lap) in 3.0-mm G450 sheet steel

	Average length of failed welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**
TFWD30.1	41	120.0	120.6	0.99
TFWD30.2	63	183.5	185.2	0.99
TFWD30.3	82	225.5	241.1	0.93
TFWD30.4	100	296.0	294.0	1.01
TFWD30.5	120	360.5	352.8	1.02

Currently, in Australia and Northern 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 Appendix III. The statistical parameters common to all types of connections tested in this paper are also given in Appendix III.

The statistical parameters required for the computation of the safety indices for the double-lap transverse fillet welded connections are given in Table 5. It was found that the safety indices β for the double-lap transverse fillet welded connections in 1.5-mm G450 sheet steel vary between 3.7 and 7.5, while those in 3.0-mm 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 5. Statistical parameters of double-lap transverse fillet welded connections

	1.5-mm specimens	**3.0-mm specimens**
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

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), 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.

4 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.

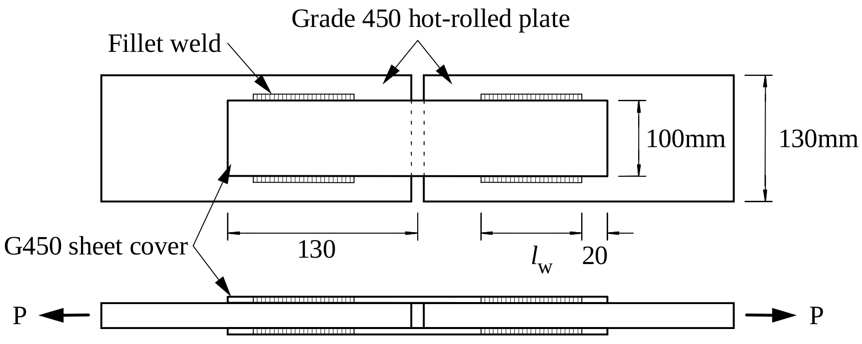

Fig. 3 Diagram of a double-lap longitudinal fillet welded connection specimen

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), 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 1.5-mm sheet steel used for the present specimens is 1.53 mm, and that of the 3.0-mm sheet steel is 2.97 mm, Equation (2a) only applies to 1.5-mm sheet specimens with welds no longer than 38 mm, and to 3.0-mm specimens with welds no longer than 74 mm.

The ultimate test loads P_t and the predicted failure loads P_p of the double-lap longitudinal fillet welded connections computed using Equation (2) are shown in Tables 6 and 7 for the 1.5-mm and the 3.0-mm 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 6. Longitudinal fillet welds (double lap) in 1.5-mm G450 sheet steel

	Average length of failed welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**
LFWD15.1	33	73.5	77.3	0.95
LFWD15.2	50	95.5	112.0	0.85
LFWD15.3	62	119.0	138.9	0.86
LFWD15.4	79	143.0	177.0	0.81
LFWD15.5	91	165.5	203.8	0.81

Table 7. Longitudinal fillet welds (double lap) in 3.0-mm G450 sheet steel

	Average length of failed welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**
LFWD30.1	42	177.5	212.1	0.84
LFWD30.2	52	207.0	252.3	0.82
LFWD30.3	61	239.0	285.0	0.84
LFWD30.4	74	286.0	326.7	0.87
LFWD30.5	83	309.0	366.1	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 8. It was found that the safety indices β for the double-lap longitudinal fillet welded connections in both the 1.5-mm and the 3.0-mm 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 8. Statistical parameters of double-lap longitudinal fillet welded connections

	1.5-mm specimens	**3.0-mm specimens**
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

Traditionally, the target index recommended for connections is set higher than that recommended for cold-formed steel 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.

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 1.5-mm sheet specimens, and between 3.4 and 6.5 for the 3.0-mm specimens. Note that the lower bound values correspond to a “live load only” case, and the safety indices quickly rise above the target index of 3.5 as the proportion of dead load increases as shown in Fig. 6.

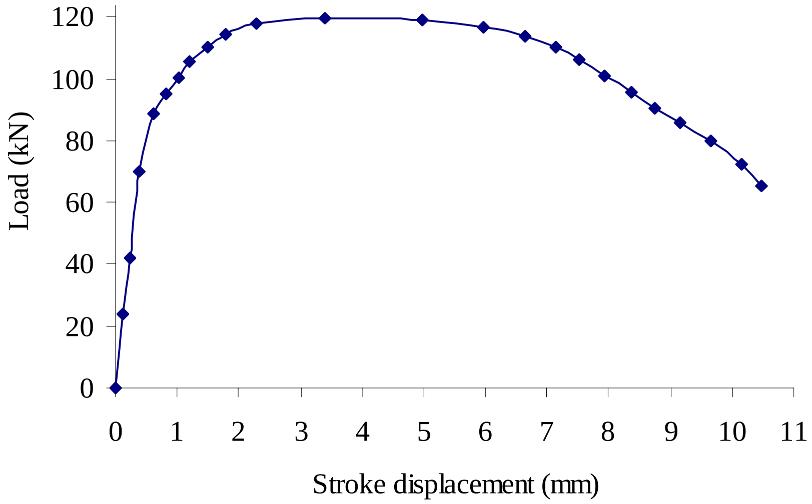

Fig. 4 Load-deflection graph of specimen LFWD15.3

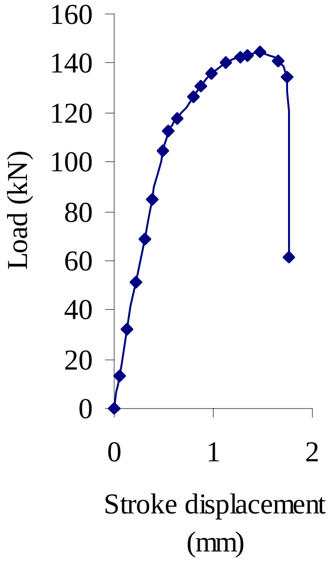

Fig. 5 Load-deflection graph of specimen HAZ15.6

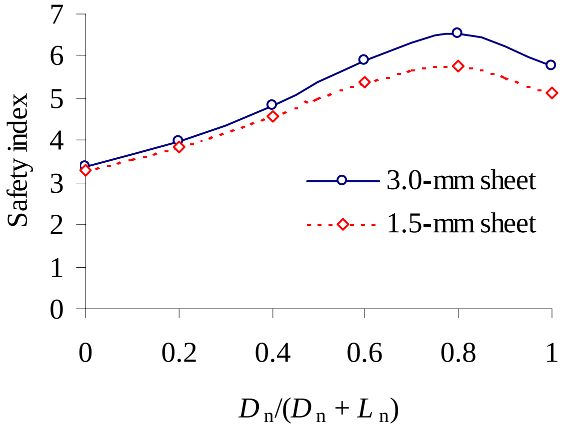

Fig. 6 Safety indices of LFWDs assuming a uniform capacity factor of 0.55

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 1.5-mm and the 3.0-mm sheet specimens, the failure modes may depend on the sheet thickness. The longitudinal fillet welded connections in the 1.5-mm sheet steel fail in the HAZs as shown in Fig. 7, while those in the 3.0-mm sheet steel fail mostly in the welds as shown in Fig. 8.

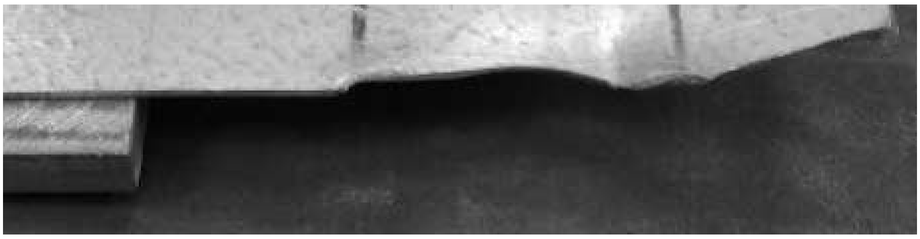

Fig. 7 HAZ failure of double-lap longitudinal fillet welded connection in 1.5-mm sheet steel

Fig. 8 Weld failure of double-lap longitudinal fillet welded connection in 3.0-mm sheet steel

The difference in failure modes is apparently due to the fact that the fillet welds in the thinner 1.5-mm cover sheets were invariably larger than the sheet thickness, while those in the thicker 3.0-mm 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 3.0-mm 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 1.5-mm and the 3.0-mm sheet specimens.

5 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 Appendix IV. Two different electrodes (0.8-mm ES6-GC/M-W503AH and 0.9-mm ES4-GC/M-W503AH) were used for the single-lap connections in 1.5-mm sheet steel as shown in the appendix. For the single-lap connections in 3.0-mm 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 1.5-mm and the 3.0-mm specimens, respectively.

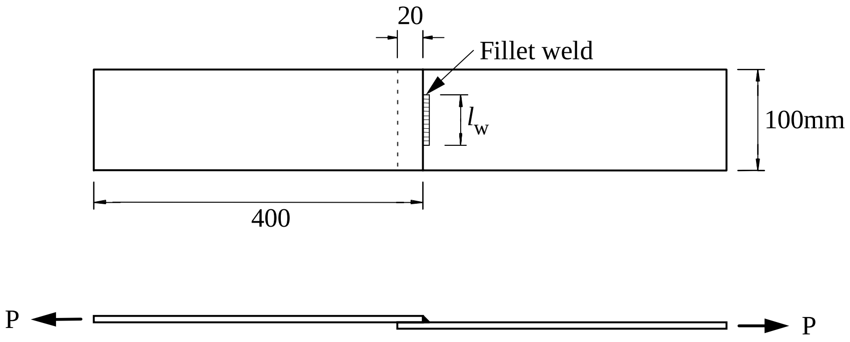

Fig. 9 Diagram of a single-lap transverse fillet welded connection specimen

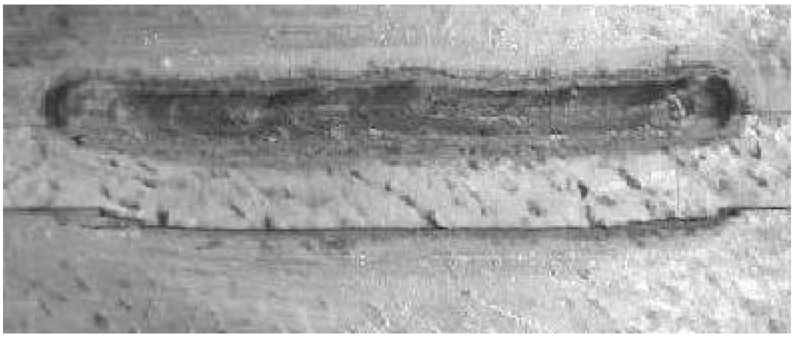

Fig. 10 HAZ failure of a single-lap transverse fillet welded connection in 1.5-mm sheet steel

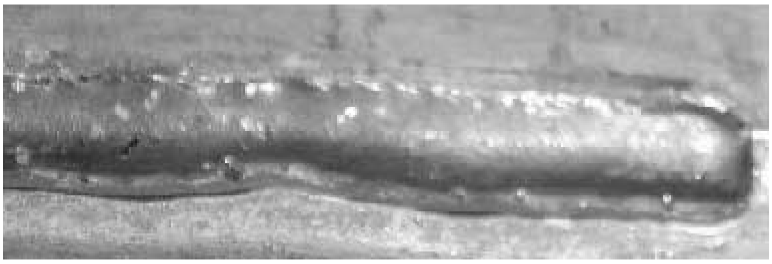

Fig. 11 HAZ failure of a single-lap transverse fillet welded connection in 3.0-mm sheet steel

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 1.5-mm sheet steel used for the present specimens is 1.49 mm, and that of the 3.0-mm sheet steel is 2.97 mm. Tables 9 and 10 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 10 that, for a single-lap connection in 3.0-mm sheet steel with a transverse fillet weld shorter than 40 mm, the inclination has insignificant effects.

Table 9. Transverse fillet welds (single-lap) in 1.5-mm G450 sheet steel

	Actual length of weld (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**	**TNO (kN)**	**P_t /TNO**
TFWS15.1	31	18.0	22.5	0.80	20.4	0.88
TFWS15.2	46	25.0	33.4	0.75	28.8	0.87
TFWS15.3	60	36.5	43.6	0.84	35.8	1.02
TFWS15.4	75	47.0	54.5	0.86	42.3	1.11
TFWS15.5	90	52.5	65.4	0.80	47.8	1.10
TFWS15.6	33	23.0	24.0	0.96	21.6	1.06
TFWS15.7	45	27.5	32.7	0.84	28.3	0.97
TFWS15.8	64	42.0	46.5	0.90	37.6	1.12
TFWS15.9	78	49.5	56.7	0.87	43.4	1.14
TFWS15.10	92	60.5	66.9	0.90	48.4	1.25

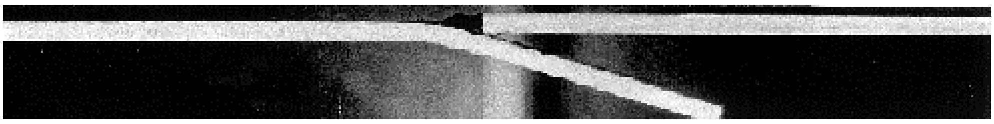

Fig. 12 Inclination of a single-lap transverse fillet welded connection in 3.0-mm sheet

Table 10. Transverse fillet welds (single-lap) in 3.0-mm G450 sheet steel

	Actual length of weld (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**	**TNO (kN)**	**P_t /TNO**
TFWS30.1	32	47.0	45.6	1.03	41.3	1.14
TFWS30.2	41	61.0	60.3	1.01	52.9	1.15
TFWS30.3	63	84.0	92.6	0.91	75.1	1.12
TFWS30.4	70	89.5	102.9	0.87	81.3	1.10
TFWS30.5	90	115.0	132.3	0.87	96.6	1.19

It can be seen from the last columns of Tables 9 and 10 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 11. It was found that the safety indices β for the connections in 1.5-mm G450 sheet steel vary between 2.9 and 4.9, while those in 3.0-mm 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 1.5-mm sheet connections, and between 3.6 and 6.1 for the 3.0-mm sheet connections.

Table 11. Statistical parameters of single-lap transverse fillet welded connections

	1.5-mm specimens	**3.0-mm specimens**
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

6 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 1.5-mm sheet, two electrodes were used for the connections in the 1.5-mm sheet steel. The welding procedures for the single-lap longitudinal fillet welds in 1.5-mm sheet steel using 0.8-mm ES6-GC/M-W503AH electrode are given in Appendix V, and those using 0.9-mm ES4-GC/M-W503AH electrode are given in Appendices IV(a) and IV(c) for the 1.5-mm and the 3.0-mm sheet specimens, respectively. Note that the single-lap connections in the 3.0-mm sheet steel used 0.8-mm wire only.

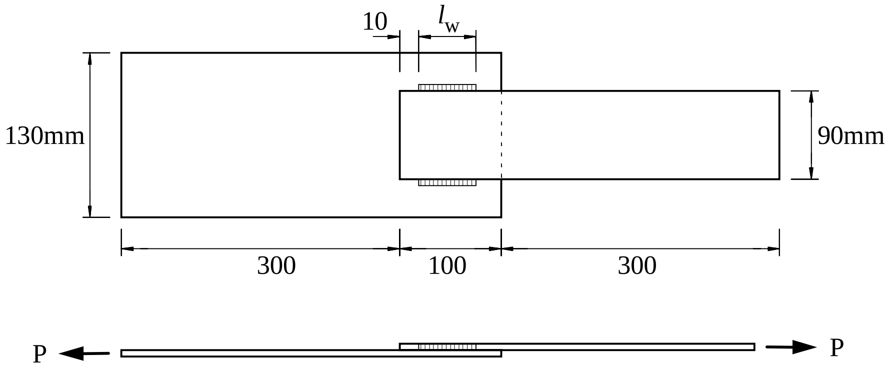

Fig. 13 Diagram of a single-lap longitudinal fillet welded connection specimen

As with the double-lap longitudinal fillet welded connections, the 1.5-mm sheet specimens failed in the HAZs (see Fig. 14) while the 3.0-mm specimens failed in the welds (see Fig. 15). However, unlike the double-lap connections, weld tearing in the 3.0-mm 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.

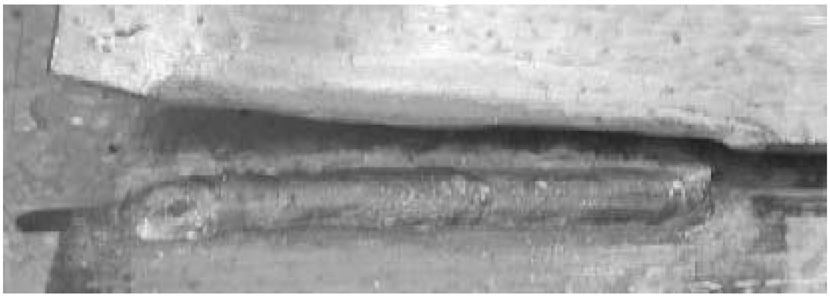

Fig. 14 HAZ failure of a single-lap longitudinal fillet welded connection in 1.5-mm sheet steel

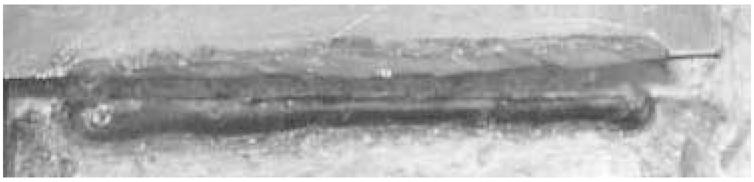

Fig. 15 Weld failure of a single-lap longitudinal fillet welded connection in 3.0-mm sheet steel

Again, despite the difference in failure mode between the 1.5-mm and the 3.0-mm sheet specimens, the ratios of ultimate test loads P_t to predicted failure loads P_p computed using Equation (2) shown in Tables 12 and 13 suggest that one design equation can be used for single-lap longitudinal fillet welded connections in the whole range of sheet thicknesses between 1.5 mm and 3.0 mm. This is because the ultimate loads of the 3.0-mm sheet specimens were reached prior to weld tearing, which means that the failure loads of the longitudinal fillet welded connections in the 1.5-mm and in the 3.0-mm sheets were controlled by the same factors.

Comparisons of the ratios P_t/P_p shown in Tables 6, 7, 12 and 13 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).

Table 12. Longitudinal fillet welds (single-lap) in 1.5-mm G450 sheet steel

	Average length of welds (mm)	***t*** **(mm)**	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**	**TNO (kN)**	**P_t /TNO**
LFWS15.1	42	1.51	36.0	46.4	0.78	45.8	0.79
LFWS15.2	52	1.51	46.5	57.5	0.81	52.9	0.88
LFWS15.3	60	1.51	49.0	66.3	0.74	57.5	0.85
LFWS15.4	71	1.51	59.5	78.5	0.76	62.3	0.96
LFWS15.5	82	1.51	68.0	90.6	0.75	65.3	1.04
LFWS15.6	53	1.50	47.0	58.6	0.80	53.5	0.88
LFWS15.7	62	1.50	54.0	68.5	0.79	58.5	0.92
LFWS15.8	70	1.50	62.5	77.4	0.81	61.9	1.01
LFWS15.9	79	1.50	66.0	87.3	0.76	64.6	1.02

Table 13. Longitudinal fillet welds (single-lap) in 3.0-mm G450 sheet steel

	Average length of welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**	**TNO (kN)**	**P_t /TNO**
LFWS30.1	42	80.5	106.0	0.76	91.4	0.88
LFWS30.2	52	98.0	126.1	0.78	105.5	0.93
LFWS30.3	63	114.5	145.9	0.78	117.6	0.97
LFWS30.4	72	130.5	160.4	0.81	124.9	1.04
LFWS30.5	82	138.0	180.8	0.76	130.2	1.06

The last columns of Tables 12 and 13 list the ratio of the ultimate test load to the predicted failure load of each specimen computed using the TNO equation (Stark & Soetens 1980)

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

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 1.5-mm sheet steel, indicate that there is no consistent deterioration in connection strength per unit length with increasing weld length.

The statistical parameters required for the computation of the safety indices of the single-lap longitudinal fillet welded connections are given in Table 14. It was found that the safety indices β for the connections in 1.5-mm G450 sheet steel vary between 3.0 and 5.5, while those in 3.0-mm 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 1.5-mm specimens, and between 3.4 and 6.7 for the 3.0-mm specimens.

Table 14. Statistical parameters of single-lap longitudinal fillet welded connections

	1.5-mm specimens	**3.0-mm specimens**
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

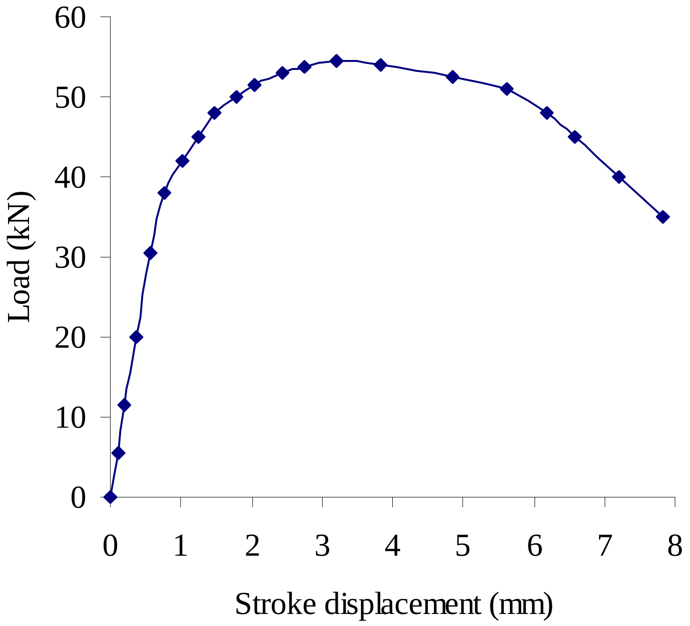

Fig. 16 Load-deflection graph of LFWS15.7

7 Note on “double-lap” and “single-lap” terms

In interpreting the results of “double-lap” and “single-lap” fillet welded connections, particularly those subjected to transverse loading, the two terms should not be taken literally. Double-lap fillet-welded connections as depicted in this paper may not be commonplace or practical, but their behaviour is representative of fillet welded connections in thin sheet steel which are not subjected to inclination typical of “unconstrained” single-lap connections depicted in this paper. Thus the design equation for “double-lap” transverse fillet welded connections is applicable to a “single-lap” sheet-to-sheet transverse fillet welded connection for which the inclination failure is effectively prevented, or which has a short weld so that inclination failure does not occur. It is also applicable to the case of a thin sheet welded to a thick plate, which could be part of a steel member.

8 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 specimens and the reliability analyses using the FOSM method, the following conclusions, which cover the full range of G450 sheet steel thicknesses between 1.5 and 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 for both 1.5-mm and 3.0-mm sheets, but is generally higher than the nominal tensile strength of 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 with a 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 with a capacity factor of 0.6, have safety indices significantly greater than 2.5. Alternatively, 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, with capacity factors of 0.6 or 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. When inclination failure governs, the connection capacity is linearly proportional to the weld length.

Appendix VI shows the statistical parameters and the reliability analysis results for all types of fillet welded connections computed using the average tensile strengths of the virgin sheet steels.

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Appendix 1a. Welding procedures for HAZ specimens in 1.5-mm G450 sheet steel

Material:	1.5-mm G450 sheet to 10-mm Grade 450 plate
Joint Type:	100-mm Transverse Fillet Weld (Double-lap)
Welding Position:	Flat (1F)
Welding Process:	GMAW, short-arc transfer
Welding Machine:	CIG Transmig 330 transformer; Transmig 2Rse feeder
Polarity:	DCEP
Stick-out:	15 mm
Electrode Trade Name:	CIG Weld Autocraft
Gas Trade Name:	Argoshield 52
Gas Composition:	23% CO_2, 77% Ar (see note at the page bottom)
Gas Flow Rate (L/min):	20

Spec. No	Electrode Classification	Wire Speed mm/min	V	A	Welding Speed mm/min	Arc Energy KJ/mm
HAZ15.1	0.9 mm ES4-GC/M-W503AH	6000	19.5	83	400	0.24
HAZ15.2			23.5	80	390	0.29
HAZ15.3			20.0	83	360	0.28
HAZ15.4			21.0	82	380	0.27
HAZ15.5			23.0	79	430	0.25
HAZ15.6		5000	19.5	129	525	0.29
HAZ15.7			19.5	129	550	0.27
HAZ15.8	0.8 mm ES6-GC/M-W503AH		20.0	108	300	0.43
HAZ15.9			20.0	108	300	0.43
HAZ15.10			19.5	163	635	0.30

Note: Specimen HAZ15.10 was welded with shielding gas composed of 60% argon, 10% carbon-dioxide, and 30% helium.

Appendix 1b. Welding procedures for HAZ specimens in 3.0-mm G450 sheet steel

Material:	3.0-mm G450 sheet to 10-mm Grade 450 plate
Joint Type:	100-mm Transverse Fillet Weld (Double-lap)
Welding Position:	Flat (1F)
Welding Process:	GMAW, short-arc transfer
Welding Machine:	CIG Transmig 330 transformer; Transmig 2Rse feeder
Polarity:	DCEP
Stick-out:	15 mm
Electrode Trade Name:	CIG Weld Autocraft
Gas Trade Name:	Argoshield 52
Gas Composition:	23% CO_2, 77% Ar (see note at the page bottom)
Gas Flow Rate (L/min):	20

Spec. No	Electrode Classification	Wire Speed mm/min	V	A	Welding Speed mm/min	Arc Energy kJ/mm
HAZ30.1	0.9 mm ES4-GC/M-W503AH	6500	21.5	198	550	0.46
HAZ30.2			21.0	188	450	0.53
HAZ30.3			22.5	188	460	0.55
HAZ30.4			21.0	188	450	0.52
HAZ30.5			22.0	185	510	0.48
HAZ30.6			22.0	185	510	0.48
HAZ30.7	0.8 mm ES6-GC/M-W503AH		22.5	150	320	0.63
HAZ30.8			22.5	150	320	0.63
HAZ30.9			21.5	180	355	0.65

Note: Specimen HAZ30.9 was welded with shielding gas composed of 60% argon, 10% carbon-dioxide, and 30% helium.

Appendix 2. Requirements for the chemical composition of G450 sheet steel

	%max
Carbon	0.20
Manganese	1.20
Phosphorous	0.04
Sulfur	0.03

Appendix 3. Reliability analysis based on FOSM method

The reliability analyses performed in this paper are based on the First Order Second Moment (FOSM) method described by Ravindra & Galambos (1978). The method assumes a log-normal distribution for the resistance R and the load Q, so that the safety index β is computed from

$$\beta = \frac{\ln\left({R_m}/{Q_m} \right)}{\sqrt{{V_R}^2 + {V_Q}^2}} \tag{3.1}$$

in which R_m is the mean resistance, Q_m is the mean load, V_R is the coefficient of variation of the resistance R, and V_Q is the coefficient of variation of the load Q.

The ratio of the mean resistance R_m to the mean load Q_m may be computed from (Zhao & Hancock 1993)

$$\frac{R_m}{Q_m} = \frac{\gamma_D\left({D_n}/{L_n} \right) + \gamma_L}{\left({D_m}/{D_n} \right)\left({D_n}/{L_n} \right) + \left({L_m}/{L_n} \right)} \frac{R_m}{R_n} \frac{1}{\phi} \tag{3.2}$$

in which γ_D is the dead load factor, D_n is the nominal dead load, L_n is the nominal live load, γ_L is the live load factor, D_m is the mean dead load, L_m is the mean live load, R_n is the nominal resistance, and ϕ is the capacity factor applied to the nominal resistance. In this paper, the ratio of the mean resistance to the mean load, R_m/Q_m, is computed as a function of the ratio D_n/L_n, so all other quantities in Equation (3.2) are constant for a particular type of connection. The exception is that for longitudinal fillet welded connections, the capacity factor ϕ may change with the ratio of the weld length to the sheet thickness.

In accordance with AS 1170.1 (SA 1993b), the dead load factor γ_D used in this paper is equal to 1.25, and the live load factor γ_L is equal to 1.50. The ratios D_m/D_n and L_m/L_n are quoted from Ellingwood et al. (1980), which are 1.05 and 1.00, respectively. The ratio R_m/R_n is equal to

$$R_m / R_n = M_m F_m P_m \tag{3.3}$$

in which M_m is the mean ratio of the actual material strength to the nominal material strength, F_m is the mean ratio of the actual geometric property to the nominal geometric property, and P_m is the mean ratio of the ultimate test loads P_t to the predicted failure loads P_p.

For unwelded (virgin) G450 sheet steel, the value of M_m has been found to be 1.187 based on mill tests conducted by BHP Coated Products over a period of 12 months from October 1995 to October 1996. However, this value of M_m is deemed inappropriate for assessing the reliability of the existing design equations for fillet welded connections in G450 sheet steels as the HAZ strengths used to predict the failure loads P_p are substantially lower than the virgin strengths. Since the value of M_m which represents the HAZs of fillet welded connections in G450 sheet steel at large is unavailable, in this paper the values of M_m are assumed to be 1.02 and 1.03 as computed from Tables 1 and 2 for the 1.5-mm and 3.0-mm sheet specimens, respectively. The coefficient of variation corresponding to M_m, denoted V_M in this paper, is assumed to be the same as that for unwelded G450 sheet steel, which is 0.03. It may be noted that the coefficients of variation computed from Tables 1 and 2 are 0.015 and 0.03, respectively.

In this paper, the value of F_m is assumed to be determined solely by the ratio of the actual sheet thickness to the nominal sheet thickness. The uncertainty in weld length is ignored as the value of F_m for fillet welds is not available to the authors. It is not appropriate to determine this value from the specimens fabricated for the present work as the workmanship is not necessarily representative of that at large. For G450 sheet steel, the value of F_m is 0.99, and the corresponding coefficient of variation V_F is 0.02.

The coefficient of variation V_R shown in Equation (3.1) is

$$V_R = \sqrt{V_M{}^2 + V_F{}^2 + V_P{}^2} \tag{3.4}$$

in which V_P is the coefficient of variation corresponding to P_m, computed for each type of connection from the ratios of ultimate test loads to predicted failure loads.

The coefficient of variation V_Q shown in Equation (3.1) is computed from

$$V_Q = \frac{\sqrt{\left({D_m}/{D_n}\right)^2 {V_D}^2 \left({D_n}/{L_n}\right)^2 + \left({L_m}/{L_n}\right)^2 {V_L}^2}}{\left({D_m}/{D_n}\right)\left({D_n}/{L_n}\right) + \left({L_m}/{L_n}\right)} \tag{3.5}$$

in which the coefficients of variation in the dead load V_D and in the live load V_L are 0.10 and 0.25, respectively (Ellingwood et al. 1980). As with the ratio of the mean resistance to the mean load, R_m/Q_m, the coefficient of variation V_Q is computed as a function of the ratio D_n/L_n.

The safety indices β of a particular type of connection can therefore be computed for cases ranging from "dead load only" to "live load only". A "live load only" case corresponds to a zero value of D_n/L_n, and a "dead load only" case corresponds to an infinite value of D_n/L_n. The latter case does not present a mathematical difficulty in computing the safety index as a very large value of D_n/L_n (say, 10^4) can be used with little loss in numerical accuracy. However, the safety indices are normally plotted against $D_n/(D_n + L_n)$, which range from zero for the "live load only" case to unity for the "dead load only" case.

The statistical parameters common to all types of fillet welded connections tested in this paper are given in Table A3.1.

Table A3.1 Statistical parameters for all types of connections

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

Appendix 4a. Welding procedures for single-lap transverse or longitudinal fillet welded connections in 1.5-mm G450 sheet using 0.9-mm wire

The individual welding procedure for each specimen of the single-lap transverse or longitudinal fillet welded connections in the 1.5-mm sheets using 0.9-mm wire (ES4-GC/M-W503AH) are not available. In their place, this appendix shows the welding procedures of two sample connections in the same sheet steel produced using the same weld settings.

Material:	1.5-mm G450 sheet to 1.5-mm G450 sheet
Joint Type:	Fillet Weld (Single-lap)
Welding Position:	Flat (1F)
Welding Process:	GMAW, short-arc transfer
Welding Machine:	CIG Transmig 330 transformer; Transmig 2Rse feeder
Polarity:	DCEP
Stick-out:	15 mm
Electrode Trade Name:	CIG Weld Autocraft
Gas Trade Name:	Argoshield 52
Gas Composition:	23% CO_2, 77% Ar
Gas Flow Rate (L/min):	20

Spec. No	Electrode Classification	Wire Speed mm/min	V	A	Welding Speed mm/min	Arc Energy kJ/mm
FWS15.1	0.9 mm ES4-GC/M-W503AH	5000	20	150	345	0.52
FWS15.2			20	155	345	0.54

Appendix 4b. Welding procedures for single-lap transverse fillet welded connections in 1.5-mm G450 sheet using 0.8-mm wire

Material:	1.5-mm G450 sheet to 1.5-mm G450 sheet
Joint Type:	Transverse Fillet Weld (Single-lap)
Welding Position:	Flat (1F)
Welding Process:	GMAW, short-arc transfer
Welding Machine:	CIG Transmig 330 transformer; Transmig 2Rse feeder
Polarity:	DCEP
Stick-out:	15 mm
Electrode Trade Name:	CIG Weld Autocraft
Gas Trade Name:	Argoshield 52
Gas Composition:	23% CO_2, 77% Ar
Gas Flow Rate (L/min):	20

Spec. No	Electrode Classification	Wire Speed mm/min	V	A	Welding Speed mm/min	Arc Energy kJ/mm
TFWS15.6	0.8 mm ES6-GC/M-W503AH	5000	21	150	350	0.54
TFWS15.7			21	150	390	0.48
TFWS15.8			21	152	550	0.35
TFWS15.9			21	155	535	0.36
TFWS15.10			21	155	550	0.35

Appendix 4c. Welding procedures for single-lap transverse or longitudinal fillet connections in 3.0-mm G450 sheet

The individual welding procedure for each specimen of the single-lap transverse or longitudinal fillet welded connections in the 3.0-mm sheets are not available. In their place, this appendix shows the welding procedures of three sample connections in the same sheet steel produced using the same weld settings.

Material:	3.0-mm G450 sheet to 3.0-mm G450 sheet
Joint Type:	Fillet Weld (Single-lap)
Welding Position:	Flat (1F)
Welding Process:	GMAW, short-arc transfer
Welding Machine:	CIG Transmig 330 transformer; Transmig 2Rse feeder
Polarity:	DCEP
Stick-out:	15 mm
Electrode Trade Name:	CIG Weld Autocraft
Gas Trade Name:	Argoshield 52
Gas Composition:	23% CO_2, 77% Ar
Gas Flow Rate (L/min):	20

Spec. No	Electrode Classification	Wire Speed mm/min	V	A	Welding Speed mm/min	Arc Energy kJ/mm
FWS30a	0.8 mm ES6-GC/M-W503AH	5000	24.5	268	600	0.66
FWS30b			24.5	265	475	0.82
FWS30c			24.5	260	535	0.71

Appendix 5. Welding procedures for single-lap longitudinal fillet connections in 1.5-mm G450 sheet using 0.8-mm wire

Material:	1.5-mm G450 sheet to 1.5-mm G450 sheet
Joint Type:	Longitudinal Fillet Weld (Single-lap)
Welding Position:	Flat (1F)
Welding Process:	GMAW, short-arc transfer
Welding Machine:	CIG Transmig 330 transformer; Transmig 2Rse feeder
Polarity:	DCEP
Stick-out:	15 mm
Electrode Trade Name:	CIG Weld Autocraft
Gas Trade Name:	Argoshield 52
Gas Composition:	23% CO_2, 77% Ar
Gas Flow Rate (L/min):	20

Spec. No	Electrode Classification	Wire Speed mm/min	V	A	Welding Speed mm/min	Arc Energy kJ/mm
LFWS15.6	0.8 mm ES6-GC/M-W503AH	5000	20.2	N/A	310	N/A
LFWS15.7			20.2	100	305	0.40
LFWS15.8			20.2	95	310	0.37
LFWS15.9			20.2	103	320	0.39

Appendix 6. Reliability analyses using the tensile strengths of virgin steels

As implied in Section 2, it is not appropriate to use the tensile strengths of the virgin sheet steels for assessing the ability of the existing design equations to predict the failure loads of the fillet welded connections. This is because the HAZ strengths of the sheet steels are significantly lower than their virgin strengths. The failure load of each fillet welded connection specimen is thus predicted using the approximate HAZ strength since the strength limit state is governed by the HAZs. It also follows that for the reliability analyses based on the test results of such specimens, it is inappropriate to use the statistical parameter M_m determined from the mill tests conducted by BHP Coated Products, Port Kembla, on virgin sheet steels.

It might be argued that for the purpose of reliability analyses, the value of M_m determined from the mill tests may be used if the predicted failure loads P_p of the specimens are computed using the tensile strengths of the virgin sheet steels. This is the procedure used in the past (Zhao & Hancock 1993) but is most likely inconsistent as the test results given in Section 2 show that the HAZ strengths in G450 sheet steels are not linearly proportional to the virgin strengths.

Nevertheless, in this appendix the predicted failure load of a specimen is computed using the average tensile strength of the virgin sheet steel, and the value of M_m for the virgin steel is used in the reliability analyses. The average tensile strength of the 1.5-mm sheet steel coupons is 596 MPa, and that of the 3.0-mm sheet steel coupons is 529 MPa. The value of M_m for the virgin G450 sheet steels was found to be 1.187 from mill tests conducted by BHP Coated Products, Port Kembla, over a period of 12 months from October 1995 to October 1996. As the strain rate employed by BHP Steel is higher than that used at the University of Sydney, the value of M_m determined from the mill tests is factored by 0.967 (CASE 1996). Strictly speaking, the factored value of M_m equal to 1.148 used in the present reliability analyses, which corresponds to a mean tensile strength of 551 MPa, may be too low for the 1.5-mm sheet steel, and too high for the 3.0-mm sheet steel.

The statistical parameters and the safety indices of the double-lap and single-lap fillet welded connections in the 1.5-mm sheet specimens tested in the present work are shown in Table A6.1. The corresponding values for the 3.0-mm sheet specimens are given in Table A6.2.

Table A6.1 Reliability analyses using a tensile strength of 596 MPa

	TFWD15	LFWD15	TFWS15	LFWS15
P_m	0.84	0.70	0.70	0.64
V_P	0.02	0.05	0.05	0.02
R_m/ R_n	0.95	0.80	0.79	0.72
V_R	0.04	0.06	0.06	0.04
β	3.4-6.7	2.7-5.3	2.7-4.5	2.7-4.8

Table A6.2 Reliability analyses using a tensile strength of 529 MPa

	TFWD30	LFWD30	TFWS30	LFWS30
P_m	0.93	0.79	0.88	0.73
V_P	0.03	0.02	0.07	0.02
R_m/ R_n	1.05	0.90	1.00	0.83
V_R	0.05	0.04	0.08	0.04
β	3.8-7.5	3.2-6.1	3.5-5.9	2.9-5.4

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