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Research Report No. R806

STRENGTH OF FLARE-BEVEL AND FLARE-VEE WELDED CONNECTIONS IN G450 SHEET STEELS

By

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ABSTRACT

This paper investigates the reliability of the existing design equations specified in AS/NZS 4600:1996 for flare-bevel and flare-vee 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 on flare-bevel welded connections only in mainly mild sheet steels. In the present work, flare-bevel and flare-vee welded connections in 1.5-mm and 3.0-mm sheet steels were fabricated using different GMAW procedures and tested to failure. All the transverse flare-bevel welded connections failed in the HAZs of the parent material. The longitudinal flare-bevel and flare-vee welded connections in 1.5-mm sheet steel also failed in the HAZs of the parent material, while those in 3.0-mm sheet steel failed in the weld metal. Nevertheless, it was found that the existing design rules may be applied conservatively to transverse and longitudinal flare-bevel welded connections in G450 sheet steels provided the weld quality is comparable to that produced in-house. On the other hand, it was found that the existing equations overestimate the capacity of flare-vee welded connections in G450 sheet steels. Ideally, flare-bevel and flare-vee welded connections in 3.0-mm G450 sheet steel are design in accordance with AS 4100. A survey of arc welded connections produced by industry fabricators suggested that the quality of in-house welded connections is unlikely to be matched in practice.

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

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1 Introduction

This paper presents the experimental program on flare-bevel and flare-vee welded connections in 1.5-mm and 3.0-mm G450 sheet steels, which followed the previously completed program on fillet welded connections (Teh & Hancock 2000). The background to this research on welded connections in cold-reduced high-strength sheet steels has been described by Teh & Hancock (2000). The objective of the present work is to verify the reliability of the design equations specified in AS/NZS 4600 (SA/SNZ 1996a) for flare-bevel and flare-vee welded connections in thin sheet steels in the case of G450 sheet steels manufactured to AS 1397 (SA 1993).

Following the approach used in the earlier work (Teh & Hancock 2000), the failure load of each specimen is predicted using the tensile strength of the heat-affected zone (HAZ). The approximate HAZ strengths of 1.5-mm and 3.0-mm G450 sheet steels were previously found to be 488 MPa and 495 MPa, respectively. These values were obtained through tensile tests on double-lap transverse fillet welded connections between G450 sheet steels and 10-mm hot-rolled steel plates of Grade 450 manufactured to AS/NZS 3678 (SA/SNZ 1996b), as depicted in Fig. 1. Such specimens failed in the heat-affected-zones of the G450 sheet steels.

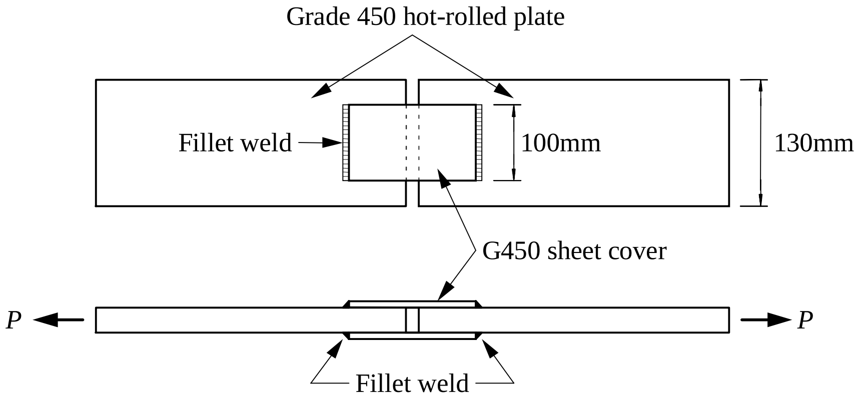

Fig. 1 Tensile test of HAZ

However, there was a concern that the relatively thick hot-rolled steel plates to which the G450 sheet steels were welded might have acted as a heat sink which limits the damage to the HAZs in the cold-reduced sheet steels, and thus the HAZ strengths so obtained might be unconservative when the sheet steels are welded to thinner materials. In order to address this concern, additional HAZ strength tests were carried out as part of the project using 6, 16 and 20 mm hot-rolled steel plates of various grades.

In the earlier work on fillet-welded connections (Teh & Hancock 2000), double-lap and single-lap connections were tested. The single-lap fillet welded connections were between the sheet steels themselves. The single-lap configuration was included in light of the test results obtained by Stark & Soetens (1980) that indicate the unreliability of the existing design equations for such connections. This indication was confirmed by Teh & Hancock (2000), especially for transverse fillet welded connections due to inclination failure of the single-lap specimens as depicted in Fig. 2. However, in practice it seems unlikely to encounter a single-lap transverse flare-bevel welded connection that allows such inclination failure. Stark & Soetens (1980) did not test any transverse flare-bevel welded connection, but used the configuration depicted in Fig. 3.

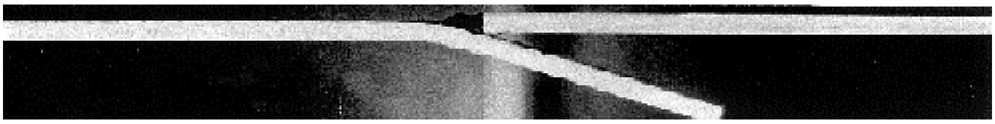

Fig. 2 Excessive inclination of a single-lap transverse fillet welded connection

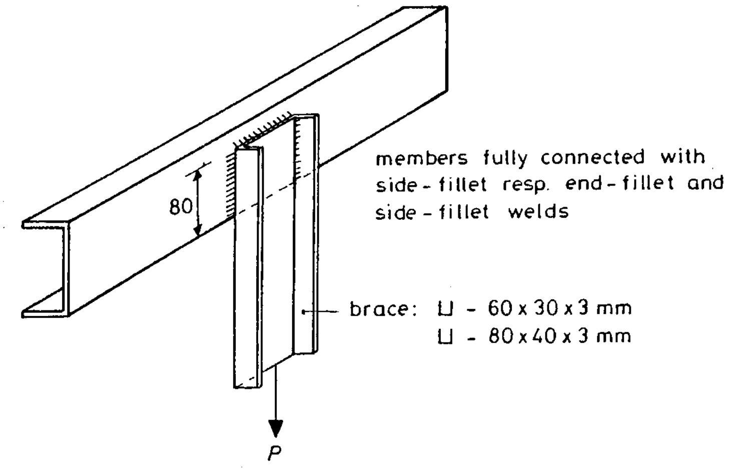

Fig 3. Configuration tested by Stark & Soetens (1980)

In the present work, double-lap and single-lap transverse flare-bevel welded connections were tested and are described in this report. However, rather than welding a channel section to a flat sheet, which would allow excessive inclination such as that illustrated in Fig. 2, the single-lap transverse flare-bevel welded connections were located between G450 sheet steel channel sections and 10-mm hot-rolled steel plates.

For flare-vee welded connections, only longitudinal loading tests were performed as described later. To the authors' knowledge, no similar tests had been carried out previously on thin sheet steels. The existing design equations for flare-vee welded connections in thin sheet steels assume those for flare-bevel welded connections (AWS 1989, SA/SNZ 1996a).

The G450 sheet steel materials used in the laboratory tests, which have a trade name GALVASPAN®[1], were manufactured and supplied by BHP Coated Steel, Port Kembla Works. 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 1993). The channel sections were manufactured by brake-pressing in the Civil Engineering workshop of the University of Sydney, as illustrated in Figs. 4 and 5.

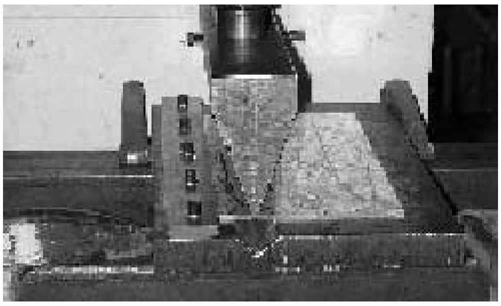

Fig. 4 Sheet steel specimen about to be brake-pressed

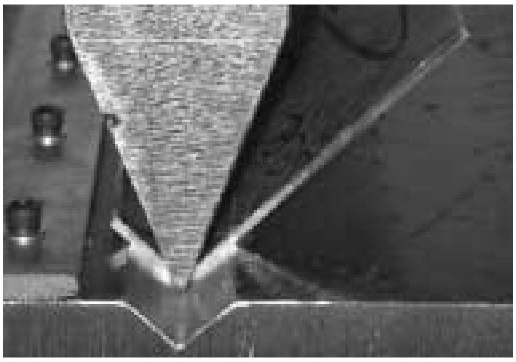

Fig. 5 Brake-pressing of sheet steel

Tensile loading of all specimens was in the rolling direction of the G450 sheet steel.

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

2 Tensile strength of HAZs

The tensile testing of HAZ specimens conducted by Teh & Hancock (2000) was repeated using 6, 16 and 20 mm hot-rolled steel plates. However, only 1.5-mm G450 sheet steel was tested as it was believed to be more susceptible to variation in the thickness of the hot-rolled steel plates. Furthermore, since the 6-mm steel plate is of Grade 250, the nominal length of all the transverse fillet welds is limited to 45 mm in order to ensure failure in the sheet steel. Previous research has indicated that non-uniform stress distribution along such a transverse fillet weld does not have significant effect on the connection strength (Teh & Hancock 2000).

Table 1 shows the ultimate test loads P_t and the "implied" HAZ strengths, computed with the assumption that the tensile stresses were uniform along the transverse fillet welds. It can be concluded from the results that the use of thicker or thinner plates does not significantly affect the tensile strength of the HAZs in G450 sheet steels. The present results also confirm the finding of the earlier work (Teh & Hancock 2000) that the HAZ strengths in G450 sheet steels are not sensitive to the variation in heat input incurred during the production of fillet welds. For the sake of "consistency" with the earlier work, the HAZ strength values used for predicting the failure loads of the flare-bevel weld specimens in the present work are assumed to be 488 MPa for the 1.5-mm sheet steel, and 495 MPa for the 3.0-mm sheet steel.

Table 1. Variation in HAZ strengths in 1.5-mm G450 sheet steel

Plate thickness (mm)	Average length of failed welds (mm)	t (mm)	P_t (kN)	$P_t/(L_w \times 2t)$ MPa	Arc energy (kJ/mm)
6	45	1.48	66.5	499	0.32
10*	41	1.51	62.5	505	0.24
16	46	1.48	68.0	499	0.38
20	45	1.48	63.5	477	0.29

*From Teh & Hancock (2000)

It may be noted that sound fillet welds in 1.5-mm G450 sheet steel have also been produced using Argoshield 54 shielding gas, and the HAZ strength was found to be similar to that reported by Teh & Hancock (2000) for fillet welds produced using Argoshield 52 shielding gas.

3 Welding procedures of flare-bevel welded connections

The detailed welding procedures for individual flare-bevel welded connection specimens discussed in the following sections are not available. However, Table 2 contains the welding procedures for several samples produced using the same settings of the GMAW machine as those used for the specimens discussed in the following sections. The welding voltage, current and time were recorded using a WeldPrint monitoring machine (Welding Technology Institute 2000). The letters BWD15 denote flare-bevel welded connections in 1.5-mm sheet steel, and the letters BWD30 denote the same in 3.0-mm sheet steel.

Table 2. Welding procedures of flare-bevel welded connections

Material:	G450 sheet steel to 10-mm Grade 450 plate
Joint Type:	Flare-Bevel Weld
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
BWD15.1	0.8 mm ES6-GC/M-W503AH	8000	21.5	153	350	0.56
BWD15.2			21.5	160	300	0.69
BWD15.3			21.5	160	345	0.60
BWD30.1		9000	26.0	175	335	0.81
BWD30.2			25.5	200	405	0.75
BWD30.3			29.0	190	420	0.79

4 Transverse flare-bevel welded connections

The double-lap specimen configuration used to verify the reliability of Clause 5.2.6.2(a) of AS/NZS 4600 (SA/SNZ 1996a) is depicted in Fig. 6. The clause is rewritten here as

$$V_w = 0.833 l_w \, t \, f_u \, ; \; \phi = 0.55 \tag{1}$$

in which V_w is the nominal capacity of a transverse flare-bevel weld of length l_w in sheet steel of average base thickness t. As indicated previously, the values of f_u are assumed to be 488 MPa for the 1.5-mm sheet steel, and 495 MPa for the 3.0-mm sheet steel. The average base metal thickness of the 1.5-mm sheet steel is 1.48 mm, and that of the 3.0-mm sheet steel is 2.97 mm.

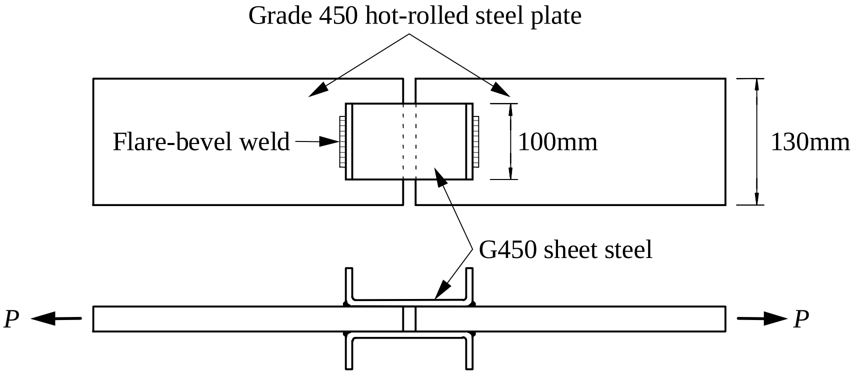

Fig. 6 Double-lap transverse flare-bevel welded connection specimen

The ultimate test load P_t and the predicted failure load P_p of each double-lap transverse flare-bevel 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) as the connections are double lap. The ultimate test loads of the present and subsequent specimens were obtained using a stroke rate of 0.2 mm/minute, which resulted in sheet strain rates of the order of 10^{-5} per second. The distance between the two grips was approximately 420 mm.

Table 3 shows that the design equation specified in Clause 5.2.6.2(a) of AS/NZS 4600 (SA/SNZ 1996a) is applicable to double-lap transverse flare-bevel welded connections in 1.5-mm G450 sheet steel, as there is generally good agreement between the predicted failure loads and the ultimate test loads.

Table 3. Transverse flare-bevel 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**
TBWD15.1	31	36.0	37.3	0.96
TBWD15.2	33	43.5	39.7	1.10
TBWD15.3	48	54.0	57.8	0.93
TBWD15.4	60	83.5	72.2	1.16
TBWD15.5	61	70.0	73.4	0.95
TBWD15.6	74	88.0	89.1	0.99
TBWD15.7	88	108.0	105.9	1.02
TBWD15.8	90	99.5	108.3	0.92

Table 4. Transverse flare-bevel 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**
TBWD30.1	32	80.0	78.4	1.02
TBWD30.2	47	108.0	115.2	0 .94
TBWD30.3	61	135.5	149.5	0.91
TBWD30.4	74	158.5	181.3	0.87
TBWD30.5	89	188.5	218.1	0.86
TBWD30.6	90	214.0	220.5	0.97

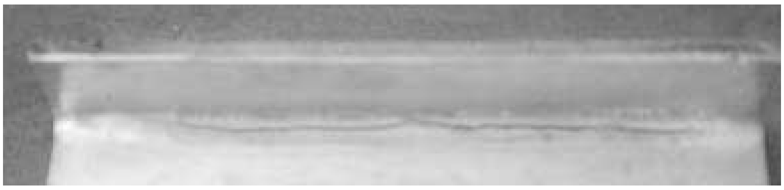

Fig. 7 HAZ failure in 3.0-mm G450 sheet steel

It is noted, however, that the nominal capacities of the 3.0-mm specimens are slightly overestimated by the design equation, although the failure modes are the same (i.e. HAZ failure as shown in Fig. 7).

In practice a capacity factor of 0.55 is specified, as indicated by Equation (1). In order to formally assess the reliability of Clause 5.2.6.2(a) of AS/NZS 4600, reliability analyses based on the First Order Second Moment method (Cornell 1969, Ravindra & Galambos 1978, Ellingwood et al. 1980) were carried out for the 1.5-mm and the 3.0-mm specimens. Description of this method and the relevant statistical parameters common to all connections in G450 sheet steels are given in Appendix I. In essence, a reliability analysis computes the safety index, normally denoted β, of a particular design equation for a certain type of "structure" from the relevant test results by taking into account the capacity factor, the load factors, and the variations in loads and in resistance. A greater value of β indicates better reliability.

The statistical parameters required for the computation of the safety indices for the double-lap transverse flare-bevel welded connections are given in Table 5. It was found that the safety indices vary between 3.8 and 6.4 for the 1.5-mm specimens, and between 3.7 and 6.6 for the 3.0-mm specimens. All these values are greater than the target index of 3.5 recommended for connections in cold-formed steel structures (SA/SNZ 1998).

Table 5. Statistical parameters of double-lap transverse flare-bevel welded connections

	1.5-mm specimens	**3.0-mm specimens**
P_m	1.00	0.93
V_P	0.08	0.06
R_m / R_n	1.01	0.95
V_R	0.09	0.07

As mentioned in the introduction, the single-lap specimens consisted of G450 sheet steel channel sections flare-bevel welded to 10-mm hot-rolled steel plates. These specimens are similar to the double-lap specimens depicted in Fig. 6, except that the channel sections are welded to one side only.

The ultimate test load P_t and the predicted failure load P_p of each single-lap transverse flare-bevel welded connection computed using Equation (1) are shown in Tables 6 and 7 for the 1.5-mm and the 3.0-mm sheet steel specimens, respectively.

Table 6. Transverse flare-bevel welds (single lap) in 1.5-mm G450 sheet steel

	Average length of failed welds (mm)	P_t **(kN)**	P_p **(kN)**	P_t / P_p
TBWS15.1	35	20.5	21.1	0.97
TBWS15.2	46	28.5	27.7	1.03
TBWS15.3	61	35.0	36.7	0.95
TBWS15.4	75	43.5	45.1	0.96
TBWS15.5	91	52.0	54.8	0.95

Table 7. Transverse flare-bevel welds (single lap) in 3.0-mm G450 sheet steel

	Average length of failed welds (mm)	P_t **(kN)**	P_p **(kN)**	P_t / P_p
TBWS30.1	30	35.5	36.7	0.97
TBWS30.2	46	55.5	56.4	0.98
TBWS30.3	60	67.0	73.5	0.91
TBWS30.4	76	77.0	93.1	0.83
TBWS30.5	90	98.0	110.3	0.89

There does not appear to be a significant difference in strength between the double-lap and the single-lap transverse flare-bevel welded connections, although limited inclination was observed in the laboratory tests. It is thus concluded that the equation specified in Clause 5.2.6.2(a) of AS/NZS 4600 (SA/SNZ 1996a) can be used to design all transverse flare-bevel welded connections in G450 sheet steels with the existing capacity factor of 0.55.

5 Longitudinal flare-bevel welded connections

The specimen configuration for a double-lap longitudinal flare-bevel welded connection is depicted in Fig. 8. It may be noted that the distance of a longitudinal flare-bevel 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 (Teh & Hancock 2000).

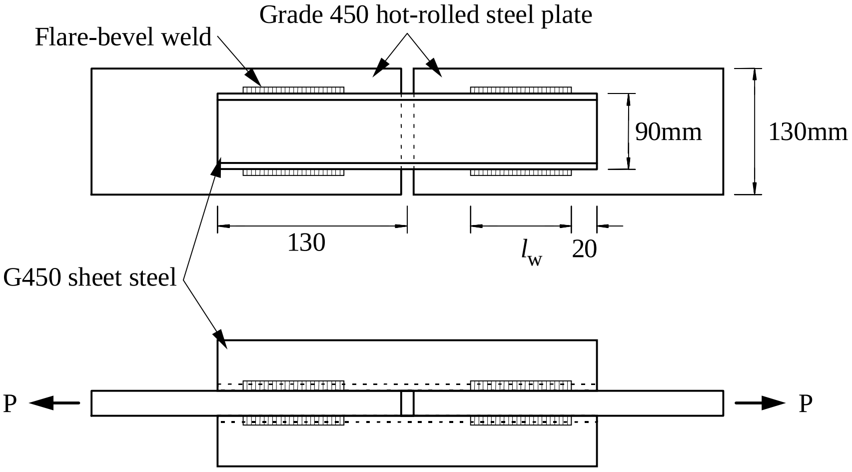

Fig. 8 Double-lap longitudinal flare-bevel welded connection specimen

The nominal capacity V_w of each weld in a longitudinal flare-bevel welded connection is specified in Clause 5.2.6.2(b) of AS/NZS 4600 (SA/SNZ 1996a), rewritten here as

(i) For $t \le t_w < 2t$ <u>or</u> if the lip height is less than weld length:

$$V_w = 0.75 l_w t f_u \text{ ; } \phi = 0.55 \tag{2a}$$

(ii) For $t_w \ge 2t$ <u>and</u> the lip height greater than weld length:

$$V_w = 1.5 l_w t f_u \text{ ; } \phi = 0.55 \tag{2b}$$

Equation (2b) is intended to account for the fact that the shear force is resisted by the web as well as the lip. For 1.5-mm sheet steel specimens, the weld throat thickness t_w is invariably larger than twice the sheet thickness t and the first condition of Equation (2b) is always fulfilled. It should also be noted that the weld metal strength is higher than the HAZ strengths of the G450 sheet steels. However, the lip height of all specimens (except for specimens LBWD15.3 and LBWD15.8) is 30 mm, so the second condition of Equation (2b) may or may not be fulfilled, depending on the weld length l_w. For 3.0-

mm sheet steel specimens, the weld throat thickness t_w is invariably smaller than twice the sheet thickness t and the first condition of Equation (2b) is never fulfilled.

The conditions for using either Equation (2a) or (2b) do not seem to have been based on rigorous theoretical study or experimental evidence. It appears that Equation (2a) is specified for the sake of conservatism. In the present work, the failure load of each specimen is first predicted using Equation (2a) in order to demonstrate its over-conservatism.

The ultimate test loads P_t and the predicted failure loads P_p of the double-lap longitudinal flare-bevel welded connections computed using Equation (2a) are shown in Tables 8 and 9 for the 1.5-mm and the 3.0-mm sheet steel specimens, respectively. It is evident from the tables that the equation significantly underestimates the failure loads of all specimens.

Table 8. Longitudinal flare-bevel welds in 1.5-mm G450 sheet steel, predicted using Equation (2a)

	Average length of failed welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**
LBWD15.1	31	123.0	67.2	1.83
LBWD15.2	34	134.5	73.7	1.83
LBWD15.3	*34	123.0	73.7	1.67
LBWD15.4	47	174.5	101.8	1.71
LBWD15.5	48	172.0	104.0	1.65
LBWD15.6	60	216.0	130.0	1.66
LBWD15.7	61	217.0	132.2	1.64
LBWD15.8	*63	219.0	136.5	1.60

*Specimen LBWD15.3 has a lip height of 50 mm, and specimen LBWD15.8 has a lip height of 20 mm.

It can also be seen from the tables that the strength of the connections is independent of the ratio of the lip height to the weld length. The slight variation in the connection strength per unit weld length is due to statistical variation as well as non-uniform stress distribution along the longitudinal welds.

Table 9. Longitudinal flare-bevel welds in 3.0-mm G450 sheet steel, predicted using Equation (2a)

	Average length of failed welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**
LBWD30.1	30	226.5	132.3	1.71
LBWD30.2	35	261.5	154.4	1.69
LBWD30.3	47	357.0	207.3	1.72
LBWD30.4	48	355.5	211.7	1.68
LBWD30.5	62	449.5	273.4	1.64

Figure 9 depicts the shearing off of the HAZs on both sides of the flare-bevel welds in the 1.5-mm sheet steel specimens. It can be seen that due to the weld throat size relative to the sheet steel thickness, and due to the lower HAZ strength compared to the weld metal strength, fracture is confined to the sheet steel. This result is similar to that of the longitudinal fillet welded connections in the same sheet steel reported by Teh & Hancock (2000). Conversely, all the flare-bevel welds in the 3.0-mm sheet steel specimens fractured in the weld metal in the post-ultimate loading region, as shown in Fig. 10. A somewhat similar phenomenon was also observed with the longitudinal fillet welded connections in the same sheet steel (Teh & Hancock 2000).

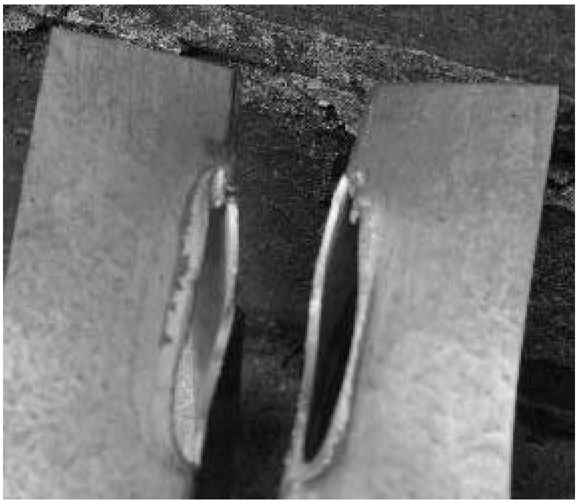

Fig. 9 HAZ failure of flare-bevel welded connection in 1.5-mm G450 sheet steel

Fig. 10 Fracture of flare-bevel welds in 3.0-mm G450 sheet steel

It is thus cautioned that Equation (2b) will not apply to longitudinal flare-bevel welded connections in 3.0-mm G450 sheet steel if the weld throats are of insufficient size. According to AS/NZS 4600 (SA/SNZ 1996a), such welded connections shall be in accordance with AS/NZS 1554.1 (SA/SNZ 2000) and their design capacity shall be determined in accordance with AS 4100 (SA 1998).

Nevertheless, comparison of the ratios P_t / P_p between Tables 8 and 9 indicates that the load capacity characteristics of the 1.5-mm and the 3.0-mm sheet specimens tested in the present work are the same. It is also interesting to compare the present results with the test results for the longitudinal fillet welded connections reported by Teh & Hancock (2000), which are reproduced here as Tables 10 and 11. It can be seen that for a given weld length, the ultimate test load of a longitudinal flare-bevel welded connection is approximately twice that of a longitudinal fillet welded connection.

Table 10. Longitudinal fillet welds (double lap) in 1.5-mm G450 sheet steel (Table 6, R802)

	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 11. Longitudinal fillet welds (double lap) in 3.0-mm G450 sheet steel (Table 7, R802)

	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 ultimate load of a longitudinal fillet or flare-bevel welded connection is associated with fracture at the tension end of the weld as depicted in Fig. 11 for a flare-bevel welded connection, which follows (and is followed by further) shear yielding of the sheet steel around the weld. This is why a longitudinal fillet welded connection behaves in a ductile manner, as reported by Teh & Hancock (2000). Naturally, a longitudinal flare-bevel welded connection also behaves in a ductile manner, as shown in Figs. 12 and 13. As mentioned previously, the shear force in a longitudinal flare-bevel welded connection is resisted by the web as well as the lip, and thus for a given weld length it is twice as strong as a longitudinal fillet welded connection.

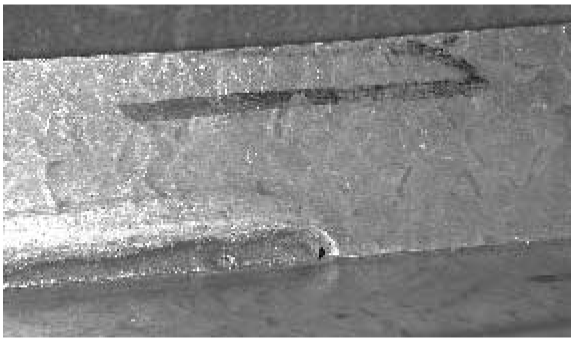

Fig. 11 Fracture at the tension end of longitudinal flare-bevel weld

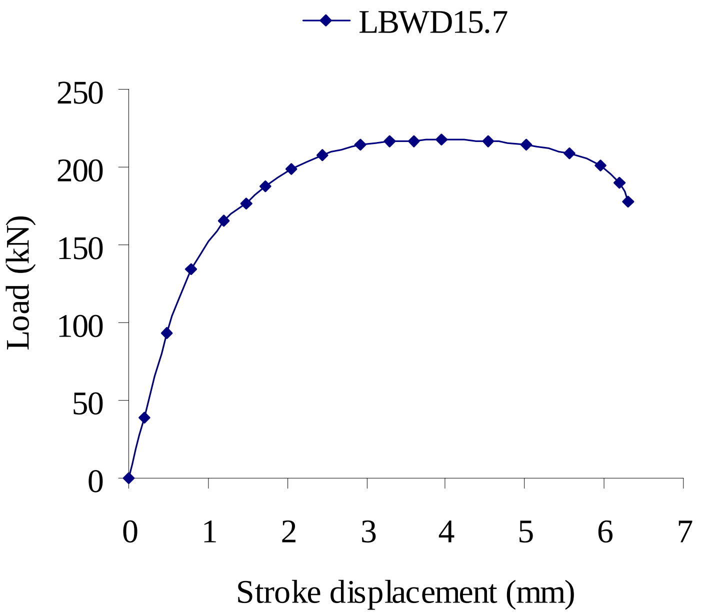

Fig. 12 Load-deflection graph of specimen LBWD15.7

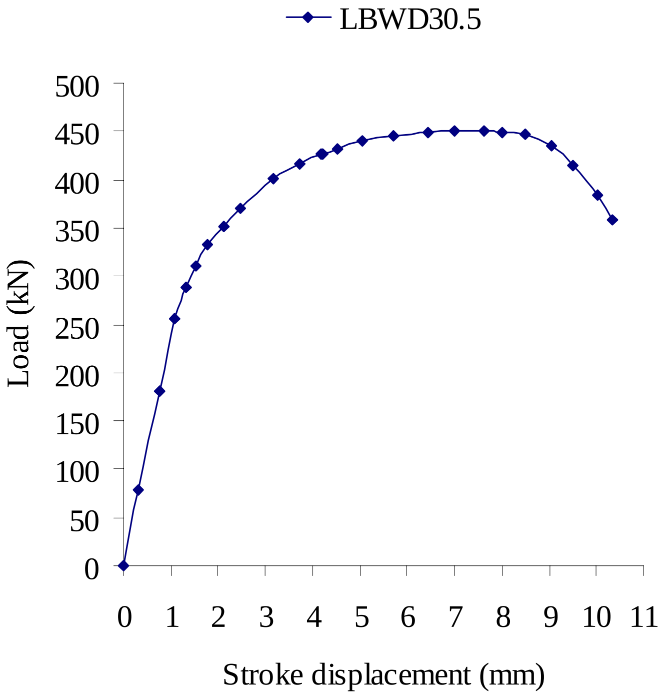

Fig. 13 Load-deflection graph of specimen LBWD30.5

Based on the discussions in the preceding paragraphs and the equation used to compute the nominal capacity of a longitudinal fillet welded connection in thin sheet steels (SA/SNZ 1996a, Teh & Hancock 2000), Equation (2b) is used to predict the failure loads of the longitudinal flare-bevel welded connections tested in the present work. The results are shown in Tables 12 and 13 for the 1.5-mm and the 3.0-mm sheet steel specimens, respectively.

Table 12. Longitudinal flare-bevel welds in 1.5-mm G450 sheet steel, predicted using Equation (2b)

	Average length of failed welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**
LBWD15.1	31	123.0	134.3	0.92
LBWD15.2	34	134.5	147.3	0.91
LBWD15.3	34	123.0	147.3	0.83
LBWD15.4	47	174.5	203.7	0.86
LBWD15.5	48	172.0	208.0	0.83
LBWD15.6	60	216.0	260.0	0.83
LBWD15.7	61	217.0	264.3	0.82
LBWD15.8	63	219.0	273.0	0.80

Table 13. Longitudinal flare-bevel welds in 3.0-mm G450 sheet steel, predicted using Equation (2b)

	Average length of failed welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**
LBWD30.1	30	226.5	264.6	0.86
LBWD30.2	35	261.5	308.7	0.85
LBWD30.3	47	357.0	414.6	0.86
LBWD30.4	48	355.5	423.4	0.84
LBWD30.5	62	449.5	546.9	0.82

The statistical parameters required for the computation of the safety indices for the double-lap longitudinal flare-bevel welded connections are given in Table 14. It was found that the safety indices vary between 3.3 and 6.1 for the 1.5-mm specimens, and between 3.4 and 6.6 for the 3.0-mm specimens. For most loading combinations, the safety indices β are greater than the target index of 3.5 recommended for connections in cold-formed steel structures (SA/SNZ 1998), as plotted in Fig. 14. 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.

Table 14. Statistical parameters of longitudinal flare-bevel welded connections

	1.5-mm specimens	**3.0-mm specimens**
P_m	0.85	0.85
V_P	0.04	0.01
R_m / R_n	0.86	0.86
V_R	0.06	0.04

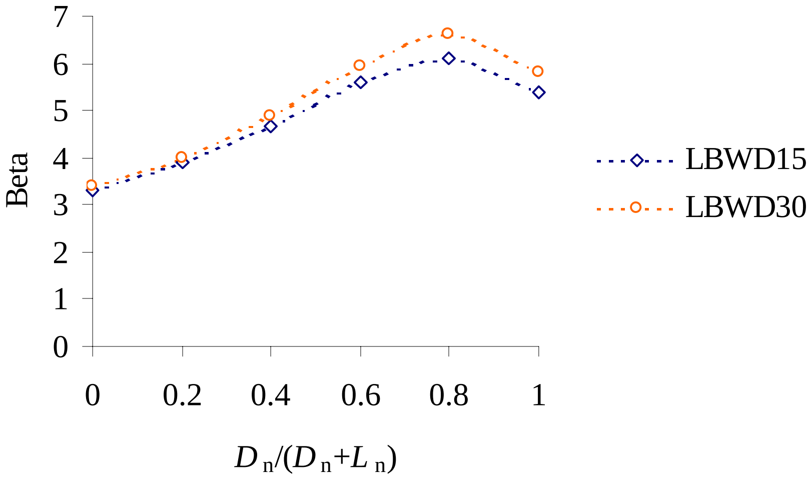

Fig. 14 Variation of safety indices β with loading combinations

The safety indices of the longitudinal flare-bevel welded connections are similar to those computed using the same capacity factor for the double-lap longitudinal fillet welded connections (Teh & Hancock 2000), although for short welds different equations are used to determine the nominal capacities of the connections.

6 Welding procedures of flare-vee welded connections

The detailed welding procedures for the individual flare-vee welded connection specimens discussed in the following section are not available. However, Table 15 contains the welding procedures for several samples. It should be noted that all specimens were welded using the same settings of the GMAW machine. The letters FVW15 and FVW30 denote flare-vee welded connections in 1.5-mm and 3.0-mm sheet steels, respectively.

Table 15. Welding procedures of flare-vee welded connections

Material:	G450 sheet steel to G450 sheet steel
Joint Type:	Flare-Vee Weld
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
FVW15.1	0.8 mm ES6-GC/M-W503AH	8500	18	135	240	0.61
FVW15.2				140	230	0.66
FVW15.3				140	235	0.64
FVW30.1		12000	26	230	675	0.53
FVW30.2				225	640	0.55
FVW30.3				225	675	0.52

7 Longitudinal flare-vee welded connections

As mentioned previously, the nominal capacity of a flare-vee weld is computed using the same design equations as those specified for a flare-bevel weld, expressed by Equation (2). To the authors' knowledge, no laboratory testing had been conducted previously to verify the applicability of those equations to flare-vee welded connections in thin sheet steels. The specimen configurations for longitudinal flare-vee welded connections in 3.0-mm and 1.5-mm G450 sheet steels are depicted in Figs. 15 and 16, respectively. The only difference between the 1.5-mm and the 3.0-mm specimens is that, for the thinner sheet steel, the lips of the middle specimens are tapered in order to avoid premature tearing at the highly-stressed intersection between the lips and the unlipped parts.

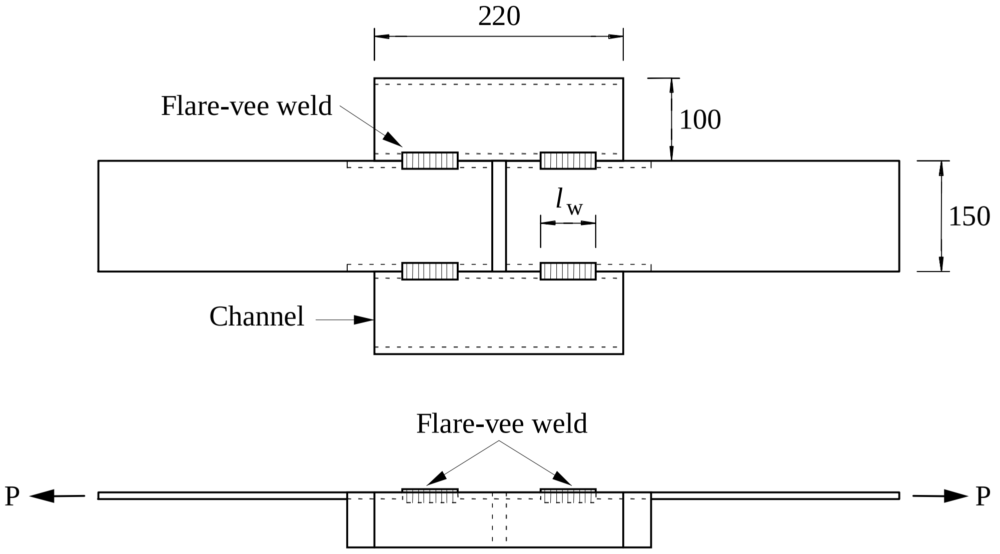

Fig. 15 Longitudinal flare-vee welded connection in 3.0-mm sheet steel

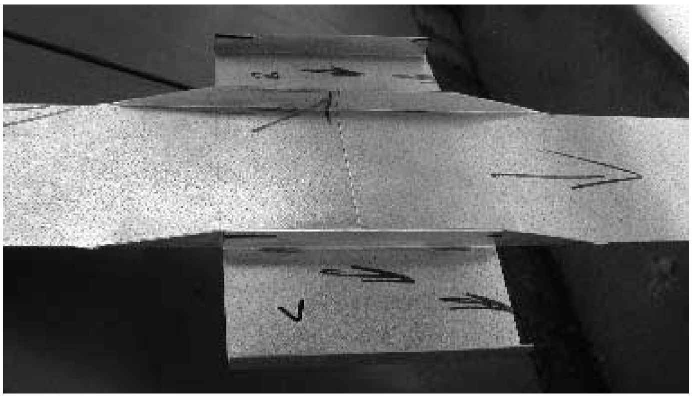

Fig 16 Tapered lips of middle sections for 1.5-mm sheet steel specimen

It was found that the 1.5-mm sheet specimens failed in the HAZs, as shown in Fig. 17. The failure mechanism is similar to that of the longitudinal flare-bevel welded connection illustrated in Fig. 11, but the longitudinal flare-vee welded connections are subjected to gross deformations as shown in Fig. 18. The 3.0-mm sheet specimens, on the other hand, failed in the weld metal as shown in Fig. 19. This is also consistent with the longitudinal flare-bevel welded connections in 3.0-mm sheet steel reported in the preceding section.

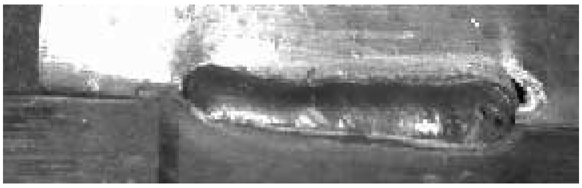
Fig. 17 HAZ failure at the tension end of a flare-vee weld in 1.5-mm sheet steel

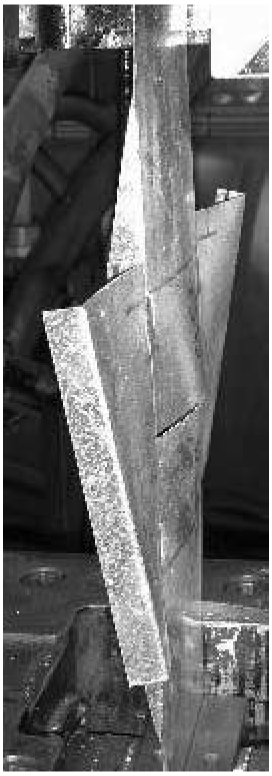
Fig. 18 Gross deformation of 1.5-mm specimen

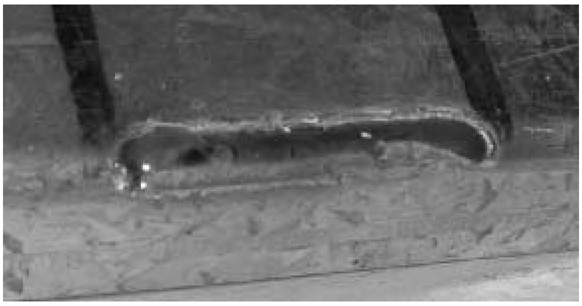

Fig. 19 Weld shear failure of flare-vee welded connection in 3.0-mm sheet steel

Following the results of the longitudinal flare-bevel welded connections reported in the preceding section, the failure loads P_p of the longitudinal flare-vee welded connections were first computed using Equation (2b). The failure loads P_p so computed and the ultimate test loads P_t are shown in Tables 16 and 17 for the 1.5-mm and the 3.0-mm sheet steel specimens, respectively.

Table 16. Longitudinal flare-vee welds in 1.5-mm G450 sheet steel, predicted using Equation (2b)

	Average length of failed welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t/P_p**
LFVW15.1	22	35.0	47.7	0.73
LFVW15.2	26	43.5	56.3	0.77
LFVW15.3	33	50.5	71.5	0.71
LFVW15.4	37	52.0	80.2	0.65
LFVW15.5	41	56.0	88.8	0.63

It is evident from Table 16 that Equation (2b) significantly overestimates the failure loads of the longitudinal flare-vee welded connections in 1.5-mm sheet steel. It can also be inferred from the ratios P_t/P_p that Equation (2a), which gives a capacity half of that given by Equation (2b), will underestimate the failure loads significantly. In order to formally assess whether the capacity factor of 0.55 specified in Equation (2b) offsets the overestimation indicated in Table 16, a reliability analysis is carried out. Table 18 lists the relevant statistical parameters. It was found that the safety indices vary between 2.5 and 4.0. These values are significantly lower than those for the longitudinal flare-bevel welded connections in the same sheet steel reported in the preceding section, which vary from 3.3 to 6.1.

Table 17. Longitudinal flare-vee welds in 3.0-mm G450 sheet steel, predicted using Equation (2b)

	Average length of failed welds (mm)	P_t (kN)	P_p (kN)	P_t / P_p
LFVW30.1	31	80.0	136.7	0.59
LFVW30.2	42	109.5	185.2	0.59
LFVW30.3	49	130.5	216.1	0.60
LFVW30.4	51	138.5	224.9	0.62
LFVW30.5	62	161.5	273.4	0.59

Table 18. Statistical parameters of longitudinal flare-vee welded connections

	1.5-mm specimens	**3.0-mm specimens**
P_m	0.70	0.60
V_P	0.06	0.01
R_m / R_n	0.705	0.61
V_R	0.07	0.04

In the earlier work on longitudinal fillet welded connections (Teh & Hancock 2000), it was 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. The argument is based on the fact that a connection loaded in the longitudinal direction of the weld behaves in a more ductile manner than a butt welded connection. If this argument is also accepted for a longitudinal flare-vee welded connection, then Equation 5.2.6.2(3) of AS/NZS 4600 (SA/SNZ 1996a) may be used to design flare-vee welded connections in 1.5-mm G450 sheet steel. It may be noted that in order to achieve a target index of 3.5 (SA/SNZ 1998), a capacity factor of 0.4 will have to be used. Alternatively, Equation

5.2.6.2(2), which is rewritten as Equation (2a) in this report, may be used with much conservatism.

It can be seen from the reliability analysis result for the 1.5-mm specimens and the statistical parameters shown in Table 18 that Equation (2b) cannot be used to design flare-vee welded connections in 3.0-mm G450 sheet steel. In fact, the safety indices for the 3.0-mm specimens were found to vary between 2.0 and 3.2. Furthermore, as mentioned previously, the ultimate load of each longitudinal flare-vee welded connection in 3.0-mm sheet steel is associated with shear failure of the weld metal itself rather than the sheet steel, as depicted in Fig. 19.

The failure loads of the longitudinal flare-vee welded connections in 3.0-mm sheet steel should therefore be computed using the following equation adapted from Clause 9.7.3.10 of AS 4100 (SA 1998)

$$V_w = 0.6\, l_w\, t_w\, f_{uw} \tag{3}$$

in which t_{w} is the weld throat thickness and f_{uw} is the tensile strength of the weld metal.

The average thickness of the weld throats across which fractures took place was found to be approximately 4 mm. Naturally, in some welds the actual thicknesses vary moderately along the weld. Nevertheless, for the purpose of the present work the weld throat thickness t_{w} used in Equation (3) is assumed to be 4 mm, which is a conservative measure as the actual average thickness is slightly less than 4 mm.

The welding electrode used in the present work is given in Table 2, which was manufactured to AS/NZS 2717.1 (SA/SNZ 1996c). Tensile tests of the weld metal were performed in accordance with AS 2205.2.2 (SA 1997), and the average tensile strength of the weld metal was found to be 512 MPa even though the nominal tensile strength is 525 MPa (CIGWELD 1993). The value of f_{uw} used in computing the failure loads shown in Table 19 is thus assumed to be 512 MPa.

It is evident from Tables 17 and 18 that for longitudinal flare-vee welded connections in 3.0-mm sheet steel, Equation (3) is a much better predictor of the failure loads than either Equation (2a) or Equation (2b).

The “inconsistency” in the laboratory test results between the longitudinal flare-vee and flare-bevel welded connections in 3.0-mm sheet steel is due to the fact that the weld throat size of a flare-bevel weld produced using the welding procedures described in Table 2 is significantly larger than that of a flare-vee weld produced using the welding procedures described in Table 15. The difference in weld throat size is also due to the relatively sharp corners of the channel sections fabricated in the present work.

Table 19. Longitudinal flare-vee welds in 3.0-mm G450 sheet steel, predicted using Equation (3)

	Average length of failed welds (mm)	**P_t (kN)**	**P_p (kN)**	**P_t / P_p**
LFVW30.1	31	80.0	76.2	1.05
LFVW30.2	42	109.5	103.2	1.06
LFVW30.3	49	130.5	120.4	1.08
LFVW30.4	51	138.5	125.3	1.11
LFVW30.5	62	161.5	152.4	1.06

A separate report (Teh & Hancock 2001) examines the strength of flare-bevel welded connections in 2.5-mm Duragal angle sections, which have a relatively large corner radius.

8 Discussions and conclusions

The existing equation specified in Clause 5.2.6.2(a) of AS 4600 may be reliably used to design transverse flare-bevel welded connections in G450 sheet steels if the welds are of the same quality as those fabricated in the present work. Strictly speaking, Clause 5.2.6.2(a) tends to overestimate the nominal capacity of the transverse flare-bevel welded connections in 3.0-mm sheet steel, but this slight overestimation is more than offset by the capacity factor of 0.55. For the specimens tested in the present work and reported in Section 4, the safety indices are comfortably above the target index of 3.5.

Equation 5.2.6.2(2) specified in Clause 5.2.6.2(b) of AS 4600 was found to be over-conservative for the longitudinal flare-bevel welded connections tested in the present work and reported in Section 5. It is possible that the lip height requirement in Clause 5.2.6.2(b) could be reduced, but further research of the effects of lip height is required to give a definite reduction.

As with longitudinal fillet welded connections reported by Teh & Hancock (2000), strictly speaking Equation 5.2.6.2(3) specified in Clause 5.2.6.2(b) overestimates the nominal capacity of the longitudinal flare-bevel welded connections by about 15%. This overestimation is offset by the capacity factor of 0.55, which results in safety indices greater than 3.5 for most loading combinations. Equation 5.2.6.2(3) may thus be used to design longitudinal flare-bevel welded connections in 1.5-mm G450 sheet steel. Notwithstanding the present reliability analysis results, the weld capacity of a longitudinal flare-bevel welded connection in 3.0-mm sheet steel should ideally be checked as required by the standard.

The use of Equation 5.2.6.2(3) specified in Clause 5.2.6.2(b) of AS 4600 to design flare-vee welded connections in 1.5-mm G450 sheet steel results in safety indices equal to or greater than 2.5. The use of Equation 5.2.6.2(2) in place of 5.2.6.2(3) ensures adequate safety indices.

However, Clause 5.2.6.2(b) was found to be inappropriate for the flare-vee welded connections in 3.0-mm sheet steel tested in the present work as failure occurred in the weld metal. This finding supports the standard requirements that such a weld be in accordance with AS/NZS 1554.1 and that the design capacity be determined in accordance with AS 4100.

The research results on fillet welded connections reported by Teh & Hancock (2000) and on flare-bevel and flare-vee welded connections reported in this paper have been based on welded connection specimens produced in the Civil Engineering workshop at the University of Sydney under good quality control. Different welding procedures were experimented with for each type of connection before the reported welding procedures were finalised. It is suspected that the in-house welded connections were of better quality than most similar connections fabricated at large, and therefore there is a need to qualify the reliability analyses reported by Teh & Hancock (2000) and in this paper. For this purpose, some specimens were sent to industry fabricators chosen at random and the results are reported in Appendix II.

Appendix I. 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

$$\beta = \frac{\ln\left({R_m}/{Q_m} \right)}{\sqrt{{V_R}^2 + {V_Q}^2}} \qquad \text{(I.1)}$$

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)

$$\frac{R_m}{Q_m} = \frac{\gamma_D \left({D_n}/{L_n} \right) + \gamma_L}{\left({D_m}/{D_n} \right)\left({D_n}/{L_n} \right) + \left({L_m}/{L_n} \right)} \frac{R_m}{R_n} \frac{1}{\phi} \qquad \text{(I.2)}$$

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 (I.2) are constant for a particular type of connection.

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

$${R_m}/{R_n} = M_m F_m P_m \qquad \text{(I.3)}$$

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 arc 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 arc 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 values of F_m for flare-bevel and for flare-vee welds are 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 in1 Equation (I.1) is

$$V_R = \sqrt{{V_M}^2 + {V_F}^2 + {V_P}^2} \qquad \text{(I.4)}$$

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 (I.1) is computed from

$$V_Q = \frac{\sqrt{\left(\frac{D_m}{D_n}\right)^2 V_D{}^2 \left(\frac{D_n}{L_n}\right)^2 + \left(\frac{L_m}{L_n}\right)^2 V_L{}^2}}{\left(\frac{D_m}{D_n}\right)\left(\frac{D_n}{L_n}\right) + \left(\frac{L_m}{L_n}\right)} \qquad \text{(I.5)}$$

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 welded connections in the present work 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 II. Fabricators' specimens

Four industry fabricators were selected at random and were asked to reproduce the transverse fillet welded connections as tested by Teh & Hancock (2000), and the transverse and longitudinal flare-bevel welded connections described in Sections 4 and 5. Each fabricator 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 Tables II.1 and II.2. The arc energies used by the industry fabricators are not available.

Table II.1 Welding wires (electrodes) of industry fabricators

Fabricator	Classification	Tensile strength (MPa)	Diameter (mm)	Wire speed (mm/min)
A	ES6-GC-W502H	525	0.9	N/A
B	AWS ER70S-6	496	0.9	4500
C	AWS ER70S-6	496	0.8	5500
D	AWS ER70S-6	496	0.9	6400

Table II.2 Shielding gases of industry fabricators

Fabricator	CO_2 (%)	Ar (%)	O_2 (%)	Flow rate (litres/min)
A	4.5	93.0	2.5	25
B	5.0	93.0	2.0	18
C	18.0	82.0	0.0	20
D	4.5	93.0	2.5	17

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 II.3 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 480 MPa specified in AS/NZS 4600

(SA/SNZ 1996a). For the purpose of comparison, the same ratios for the specimens tested by Teh & Hancock (2000) and reported in Sections 4 and 5 are also included in the table. The connection designations used in Table II.3 are consistent with those used by Teh & Hancock (2000) and in Sections 4 and 5.

Fabricator	**TFWD15**	**TFWD30**	**TBWD15**	**TBWD30**	**LBWD15**	**LBWD30**
In-house*	1.04	1.02	1.04	0.94	0.86	0.86
A	1.07	0.98	0.72	0.81	0.86	0.71
B	0.91	0.95	0.96	1.06	0.88	0.90
C	1.01	0.54	0.89	0.74	0.84	0.70
D	0.30	0.84	0.84	0.76	0.82	0.69

*Average values for specimens tested, computed using the nominal tensile strength of 480 MPa

It is evident from Table II.3 that only Fabricator B produced welded connections comparable to the in-house specimens, although the welds were grossly oversized and were the "worst looking" as shown in Fig. II.1. The fillet weld shown in Fig. II.1 may not be acceptable in practice because of its excessive size.

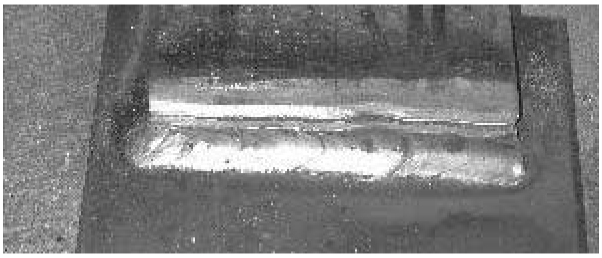

Fig. II.1 Fillet weld in 3.0-mm sheet steel produced by Fabricator B

The next best specimens were produced by Fabricator A, who appears to have some difficulty with flare-bevel welds. It is also of interest to note that the transverse fillet welded connection in 3.0-mm sheet steel (TFWD30) produced by this fabricator failed in the weld as shown in Fig. II.2, although the ultimate test load was found to be close to the nominal capacity and was the highest among the industry fabricators'. Interestingly too, this is the only fillet weld that fractured in the tests and was the only one produced using an electrode that complies with the welding consumables requirement specified in AS/NZS 1554.1 (SA/SNZ 2000) for G450 sheet steel.

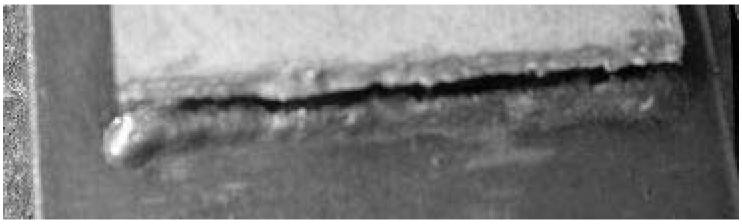

Fig. II.2 Fillet weld in 3.0-mm sheet steel produced by Fabricator A

The transverse fillet welded connection in 3.0-mm sheet steel produced by Fabricator C failed at half the expected ultimate load. This is due to the lack of fusion as evident from Fig. II.3, 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 fillet welds be subjected to macro test. The surface “crater” to the left of the boundary between the fillet weld and the sheet steel might suggest internal porosity of the weld metal.

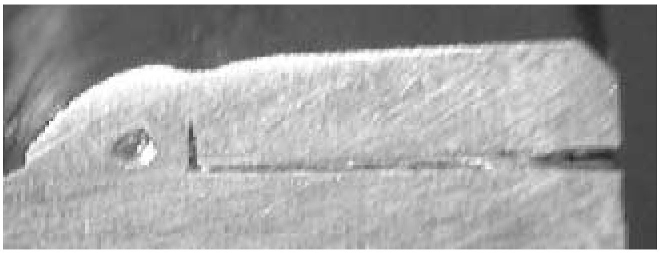

Fig. II.3 Lack of fusion in Fabricator C’s fillet weld

The transverse fillet welded connection in 1.5-mm sheet steel produced by Fabricator D failed at one third of the expected ultimate load. 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 penetration along the weld (see Fig. II.4). This is also the explanation for the relatively low ultimate test load of the fillet welded connection in 3.0-mm sheet steel produced by the same fabricator. This result indicates that macro test as a pre-qualification procedure for fillet welds should be complemented with the destructive testing illustrated in Fig. II.5, as required by the AWS D1.3 Structural Welding Code (AWS 1989).

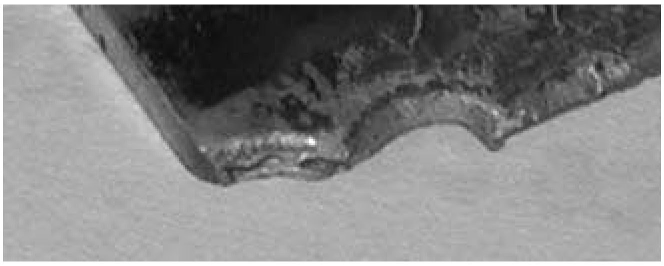

Fig. II.4 Uneven fillet weld penetration

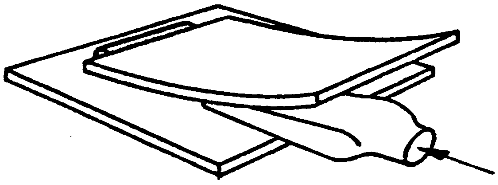

Fig. II.5 Destructive testing of fillet weld

It is not easy to determine why the transverse flare-bevel welded connections produced by Fabricators A, C and D failed at significantly lower loads compared with those produced in-house. From visual inspection, these fabricators' flare-bevel welds appeared satisfactory, as shown in Fig. II.6. Note also that all except for the connection in 3.0-mm sheet steel (TBWD30) produced by Fabricator D failed in the HAZs of the G450 sheet steel, at exactly the corners of the channel sections. It is possible that the highly cold-worked corners of the channel sections are more sensitive to welding heat input, and thus might have significantly lower HAZ strengths compared to the HAZs of the flat sheet steels.

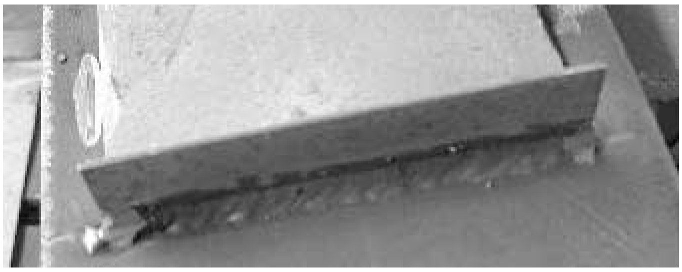

Fig. II.6 Flare-bevel weld in 1.5-mm sheet steel produced by Fabricator A

The longitudinal flare-bevel welded connections in 1.5-mm sheet steel is the only type of connection for which consistent results were obtained from all fabricators. This phenomenon may be attributed to the failure mechanism of such connections as described in Section 5 and illustrated in Fig. 11. Provided the weld fusion is satisfactory, such a connection will always fracture in the sheet steel at the tension end of the longitudinal welds.

Except for the specimen of Fabricator B, which had grossly oversized welds as shown in Fig. II.7 (the lip height is 20 mm), all the longitudinal flare-bevel welded connections in 3.0-mm sheet steel produced by the industry fabricators failed at significantly lower loads relative to the in-house specimens. The specimens of Fabricators A, C and D have noticeably smaller weld throats compared with the in-house welds (see Fig. II.8). Also, the specimens of Fabricators C and D were produced using an electrode that does not comply with Clause 4.6.1.1 of AS/NZS 1554.1 (SA/SNZ 2000), as shown in Table II.1.

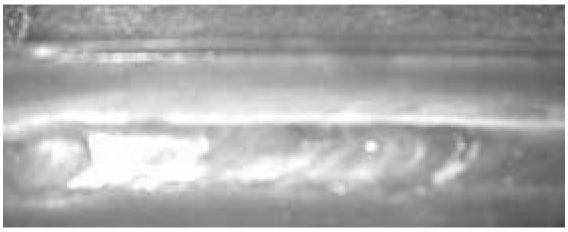

Fig. II.7 Flare-bevel weld in 3.0-mm sheet steel produced by Fabricator B

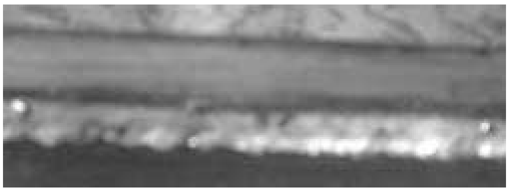

Fig. II.8 Flare-bevel weld in 3.0-mm sheet steel produced by Fabricator C

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