Strength and Behavior of Flare-bevel and Flare-vee Welded Connections in G450 Sheet Steel

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Abstract

G450 steel to AS 1397 is a cold-reduced sheet steel with in-line galvanizing. Its grade is 65 ksi (450 MPa) yield and 70 ksi (480 MPa) tensile strength. It is widely used in Australia for purlins, and is being used to fabricate light-weight portal frames, often by welding. The effect of welding on G450 sheet steel in the heat affected zone (HAZ) was unknown and so the project was performed to investigate the strength of flare-bevel and flare-vee welded connections. Flare-bevel and flare-vee welded connections in 0.06-in (1.5-mm) and 0.12-in (3.0-mm) sheet steels were tested to failure. The failure modes and ductility of different types of connections are described. The test results are used to check the design rules in the AISI Specification (Section E2.5) and the Australian/New Zealand Standard for Cold-Formed Steel Structures AS/NZS 4600 (Clause 5.2.6). Connections in 0.12-in (3.0-mm) sheet steel failed in the weld and it is important that these connections are checked for weld throat failure, not just parent material failure. The quality of flare-bevel welded connections in thin sheet steels produced by industry fabricators is investigated. The results of this study have recently been incorporated into the AISI Specification for Cold-Formed Steel Structures by reducing the thickness at which weld throat failure should be checked to 2.5 mm (0.10 in).

Introduction

This paper presents the experimental program on flare-bevel and flare-vee welded connections in 0.06-in (1.5-mm) and 0.12-in (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, 2002), the failure load of each specimen is predicted using the tensile strength of the heat-affected zone (HAZ). The approximate HAZ strengths of 0.06-in (1.5-mm) and 0.12-in (3.0-mm) G450 sheet steels were previously found to be 70.8 ksi (488 MPa) and 71.8 ksi (495 MPa), respectively.

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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 the inclination failure of the single-lap specimens as depicted in Fig. 1. 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. 2.

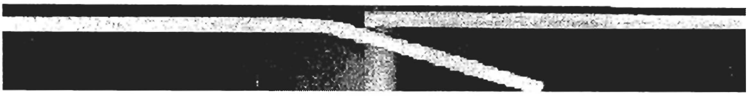

Fig. 1 Excessive inclination of a single-lap transverse fillet welded connection

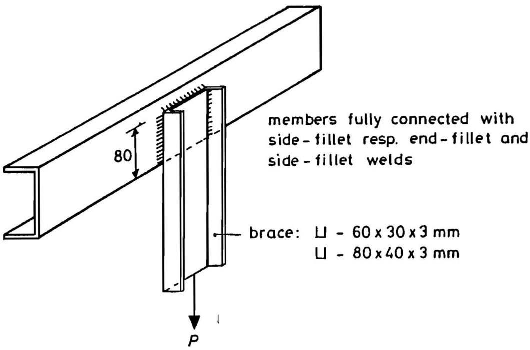

Fig. 2 Configuration tested by Stark & Soetens (1980)

In the present work, double-lap and single-lap transverse flare-bevel welded connections are tested as 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. 1, the single-lap transverse flare-bevel welded connections are located between G450 sheet steel channel sections and 4-in (10-mm) hot-rolled steel plates.

For flare-vee welded connections, only longitudinal loading tests are 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, AISI 1996).

The G450 sheet steel materials used in the laboratory tests, which have a trade name GALVASPAN®[3], were manufactured and supplied by BHP Coated Steel, Port Kembla Works.

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

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 Fig. 3.

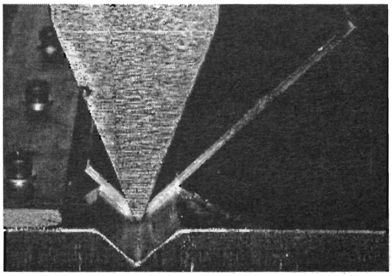

Fig. 3 Brake-pressing of sheet steel

Tensile loading of all specimens was in the rolling direction of the G450 sheet steel. The welding procedures are given in Teh & Hancock (2001a).

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), or Section E2.5(a) of AISI Specification (AISI 1996), is depicted in Fig. 4. The clause is rewritten here as

$$V_w = 0.833 l_w t f_u ; \phi = 0.55 \quad (1)$$

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 70.8 ksi (488 MPa) for the 0.06-in (1.5-mm) sheet steel, and 71.8 ksi (495 MPa) for the 0.12-in (3.0-mm) sheet steel. The average base metal thickness of the 0.06-in sheet steel is 1.48 mm, and that of the 0.12-in sheet steel is 2.97 mm.

The ratios of the ultimate test loads P_t of the double-lap transverse flare-bevel welded connections to the predicted failure loads P_p computed using Equation (1) are shown in Tables 1 and 2 for the 0.06-in (1.5-mm) and the 0.12-in (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 0.008 in/minute (0.2 mm/minute), which resulted in sheet strain rates of the order of 10^{-5} per second.

Table 1 shows that the design equation specified in Clause 5.2.6.2(a) of AS/NZS 4600 (SA/SNZ 1996a), or Section E2.5(a) of AISI Specification (AISI 1996), is applicable to double-lap transverse flare-bevel welded connections in 0.06-in (1.5-mm) G450 sheet steel, as there is generally good agreement between the predicted failure loads and the ultimate test loads.

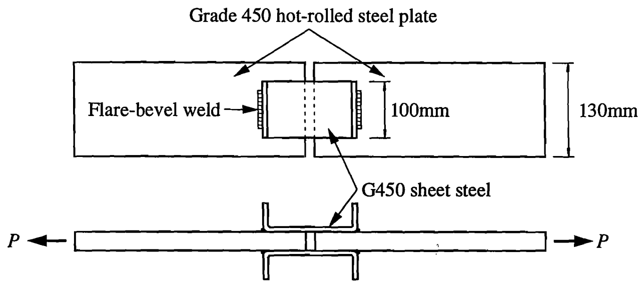

Fig. 4 Double-lap transverse flare-bevel welded connection specimen

Table 1 Transverse flare-bevel welds (double lap) in 0.06-in G450 sheet steel

	Average length of failed welds		P_t / P_p
	in	**mm**	
TBWD15.1	1.22	31	0.96
TBWD15.2	1.30	33	1.10
TBWD15.3	1.89	48	0.93
TBWD15.4	2.36	60	1.16
TBWD15.5	2.40	61	0.95
TBWD15.6	2.91	74	0.99
TBWD15.7	3.46	88	1.02
TBWD15.8	3.54	90	0.92

Table 2 Transverse flare-bevel welds (double lap) in 0.12-in G450 sheet steel

	Average length of failed welds		P_t / P_p
	in	**mm**	
TBWD30.1	1.26	32	1.02
TBWD30.2	1.85	47	0.94
TBWD30.3	2.40	61	0.91
TBWD30.4	2.91	74	0.87
TBWD30.5	3.50	89	0.86
TBWD30.6	3.54	90	0.97

It is noted, however, that the nominal capacities of the 0.12-in (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. 5).

Fig. 5 HAZ failure in 0.12-in G450 sheet steel

In practice a capacity factor of 0.55 is specified, as indicated by Equation (1). In order to formally assess the reliability of Equation (1), reliability analyses based on the First Order Second Moment method (Cornell 1969, Ravindra & Galambos 1978, Ellingwood et al. 1980) were carried out for the 0.06-in and the 0.12-in specimens. Description of this method and the relevant statistical parameters common to all connections in G450 sheet steels are given in Teh & Hancock (2001a). 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. In the present work, the value of β is computed using equation C-A6.1.1-2 of the commentary to the AISI Specification (AISI 1996).

The statistical parameters required for the computation of the safety indices for the double-lap transverse flare-bevel welded connections are given in Table 3 and Appendix I. It was found that the safety indices vary between 3.8 and 6.4 for the 0.06-in specimens, and between 3.7 and 6.6 for the 0.12-in 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 3 Statistical parameters of double-lap transverse flare-bevel welded connections

	0.06-in	**0.12-in**
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
ϕ	0.55	0.55
β	3.8-6.4	3.7-6.6

P_m = mean value of P_t/P_p

V_P = coefficient of variation of P_t/P_p

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

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

As mentioned in the introduction, the single-lap specimens consisted of G450 sheet steel channel sections flare-bevel welded to 4-in (10-mm) hot-rolled steel plates. These specimens are similar to the double-lap specimens depicted in Fig. 4, except that the channel sections are welded to one side only. The ratios of the predicted failure loads P_p computed using Equation (1) to the ultimate test loads P_t of each single-lap transverse flare-bevel welded connection are shown in Tables 4 and 5 for the 0.06-in and the 0.12-in sheet steel specimens, respectively.

Table 4 Transverse flare-bevel welds (single lap) in 0.06-in G450 sheet steel

	Average length of failed welds		P_t / P_p
	in	**mm**	
TBWS15.1	1.38	35	0.97
TBWS15.2	1.81	46	1.03
TBWS15.3	2.40	61	0.95
TBWS15.4	2.95	75	0.96
TBWS15.5	3.58	91	0.95

Table 5 Transverse flare-bevel welds (single lap) in 0.12-in G450 sheet steel

	Average length of failed welds		P_t / P_p
	in	**mm**	
TBWS30.1	1.18	30	0.97
TBWS30.2	1.81	46	0.98
TBWS30.3	2.36	60	0.91
TBWS30.4	2.99	76	0.83
TBWS30.5	3.54	90	0.89

There does not appear to be a significant difference in the ratios of the ultimate test loads to predicted failure loads 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), or Section E2.5(a) of AISI Specification (AISI 1996), can be used to design all transverse flare-bevel welded connections in G450 sheet steels with the existing capacity factor of 0.55.

Longitudinal flare-bevel welded connections

The specimen configuration for a double-lap longitudinal flare-bevel welded connection is depicted in Fig. 6. 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.

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), or Section E2.5(b) of AISI Specification (AISI 1996), rewritten here as

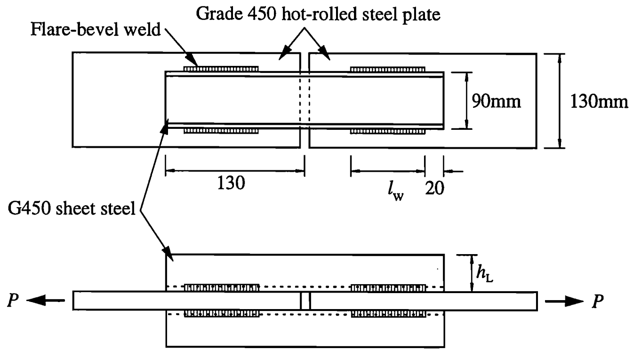

Fig. 6 Double-lap longitudinal flare-bevel welded connection specimen

(i) For $t \leq t_w < 2t$ or 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 $t_w \geq 2t$ and 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 0.06-in (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 1.2 in (30 mm), so the second condition of Equation (2b) may or may not be fulfilled, depending on the weld length l_w. For 0.12-in (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 ratios of the ultimate test loads P_t of the double-lap longitudinal flare-bevel welded connections to the predicted failure loads P_p computed using Equation (2a) are shown in Tables 6 and 7 for the 0.06-in and the 0.12-in sheet steel specimens, respectively. The predicted failure loads P_p is four times V_w in Equation (2a). It is evident from the tables that the equation significantly underestimates the failure loads of all specimens.

Table 6 Longitudinal flare-bevel welds in 0.06-in G450 sheet steel, predicted using Equation (2a)

	Average length of failed welds		h_L/l_w	P_t (kN)	P_t / P_p
	in	**mm**			
LBWD15.1	1.22	31	0.97	123.0	1.83
LBWD15.2	1.34	34	0.88	134.5	1.83
LBWD15.3	*1.34	*34	1.47	123.0	1.67
LBWD15.4	1.85	47	0.64	174.5	1.71
LBWD15.5	1.89	48	0.63	172.0	1.65
LBWD15.6	2.36	60	0.50	216.0	1.66
LBWD15.7	2.40	61	0.49	217.0	1.64
LBWD15.8	*2.48	*63	0.32	219.0	1.60

*LBWD15.3 has a lip height h_L of 2 in (50 mm), and LBWD15.8 has a lip height h_L of 0.8 in (20 mm)

Table 7 Longitudinal flare-bevel welds in 0.12-in G450 sheet steel, predicted using Equation (2a)

	Average length of failed welds		h_L/l_w	P_t (kN)	P_t / P_p
	in	**mm**			
LBWD30.1	1.18	30	1.00	226.5	1.71
LBWD30.2	1.38	35	0.86	261.5	1.69
LBWD30.3	1.85	47	0.64	357.0	1.72
LBWD30.4	1.89	48	0.63	355.5	1.68
LBWD30.5	2.44	62	0.48	449.5	1.64

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.

Figure 7 depicts the shearing off of the HAZs on both sides of the flare-bevel welds in the 0.06-in (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 (2002). Conversely, all the flare-bevel welds in the 0.12-in (3.0-mm) sheet steel specimens fractured in the weld metal in the post-ultimate loading region, as shown in Fig. 8. A somewhat similar phenomenon was also observed with the longitudinal fillet welded connections in the same sheet steel (Teh & Hancock 2002).

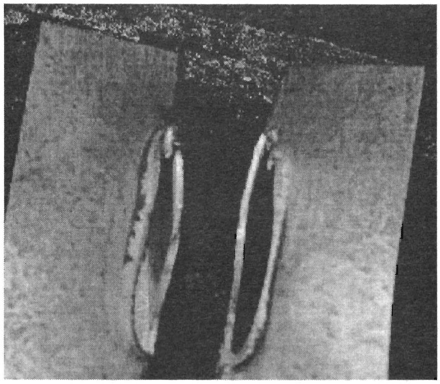

Fig. 7 HAZ failure of flare-bevel welded connection in 0.06-in G450 sheet steel

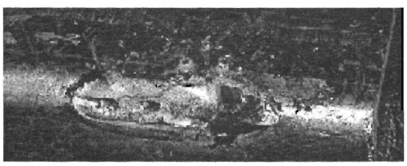

Fig. 8 Fracture of flare-bevel welds in 0.12-in G450 sheet steel

It is thus cautioned that Equation (2b) will not apply to longitudinal flare-bevel welded connections in 0.12-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 6 and 7 indicates that the use of Equation (2a) to predict the failure loads of the 0.06-in (1.5-mm) and the 0.12-in (3.0-mm) sheet specimens tested in the present work produced similar results. It is also interesting to compare the present results with the test results for the longitudinal fillet welded connections reported by Teh & Hancock (2002), which are reproduced here as Tables 8 and 9. It can be seen that for a given weld length, the ultimate test load P_t of a longitudinal flare-bevel welded connection is almost twice that of a longitudinal fillet welded connection.

Table 8 Longitudinal fillet welds (double lap) in 0.06-in G450 sheet steel

	Average length of failed welds		P_t (kN)
	in	**mm**	
LFWD15.1	1.30	33	73.5
LFWD15.2	1.97	50	95.5
LFWD15.3	2.44	62	119.0
LFWD15.4	3.11	79	143.0
LFWD15.5	3.58	91	165.5

Table 9 Longitudinal fillet welds (double lap) in 0.12-in G450 sheet steel

	Average length of failed welds		P_t (kN)
	in	**mm**	
LFWD30.1	1.65	42	177.5
LFWD30.2	2.05	52	207.0
LFWD30.3	2.40	61	239.0
LFWD30.4	2.91	74	286.0
LFWD30.5	3.27	83	309.0

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. 9 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 (2002). Naturally, a longitudinal flare-bevel welded connection also behaves in a ductile manner, as shown in Fig. 10. 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.

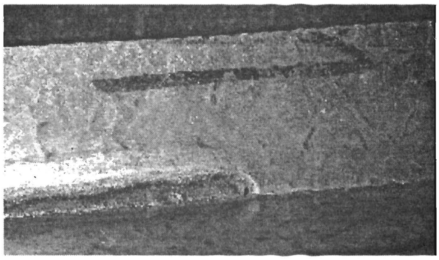

Fig. 9 Fracture at the tension end of longitudinal flare-bevel weld

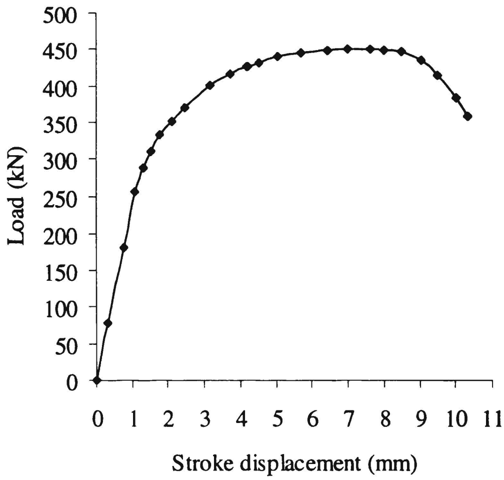

Fig. 10 Load-deflection graph of specimen LBWD30.5

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, 2002), 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 10 and 11 for the 0.06-in (1.5-mm) and the 0.12-in (3.0-mm) sheet steel specimens, respectively.

The statistical parameters required for the computation of the safety indices for the double-lap longitudinal flare-bevel welded connections are given in Table 12 and Appendix I. 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. 11. 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 10 Longitudinal flare-bevel welds in 0.06-in G450 steel, predicted using Equation (2b)

	Average length of failed welds		P_t / P_p
	in	**mm**	
LBWD15.1	1.22	31	0.92
LBWD15.2	1.34	34	0.91
LBWD15.3	*1.34	*34	0.83
LBWD15.4	1.85	47	0.86
LBWD15.5	1.89	48	0.83
LBWD15.6	2.36	60	0.83
LBWD15.7	2.40	61	0.82
LBWD15.8	*2.48	*63	0.80

Table 11 Longitudinal flare-bevel welds in 0.12-in G450 steel, predicted using Equation (2b)

	Average length of failed welds		P_t / P_p
	in	**mm**	
LBWD30.1	1.65	42	0.86
LBWD30.2	2.05	52	0.85
LBWD30.3	2.40	61	0.86
LBWD30.4	2.91	74	0.84
LBWD30.5	3.27	83	0.82

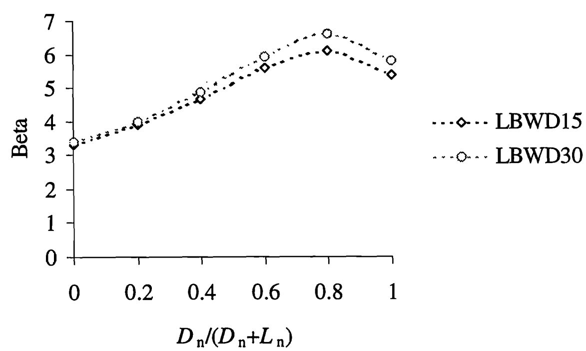

Fig. 11 Variation of safety indices β with loading combinations

Table 12 Statistical parameters of longitudinal flare-bevel welded connections

	0.06-in	0.12-in
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
ϕ	0.55	0.55
β	3.3-6.1	3.4-6.6

P_m = mean value of P_t/P_p

V_P = coefficient of variation of P_t/P_p

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

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

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 2002), although for short welds different equations are used to determine the nominal capacities of the connections.

Longitudinal flare-vee welded connections

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 0.12-in (3.0-mm) and 0.06-in (1.5-mm) G450 sheet steels are depicted in Figs. 12 and 13, respectively. The only difference between the 0.06-in and the 0.12-in specimens is that, for the thinner sheet steel, the lips of the middle specimens were tapered (see Fig. 13) in order to avoid premature tearing at the highly-stressed intersection between the lips and the unlipped parts.

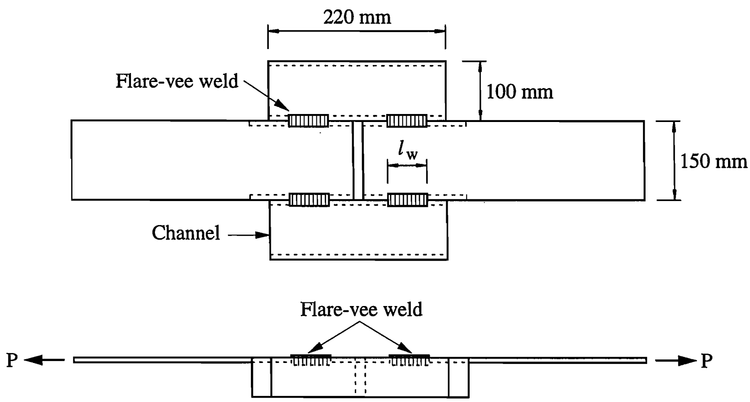

Fig. 12 Longitudinal flare-vee welded connection in 0.12-in sheet steel

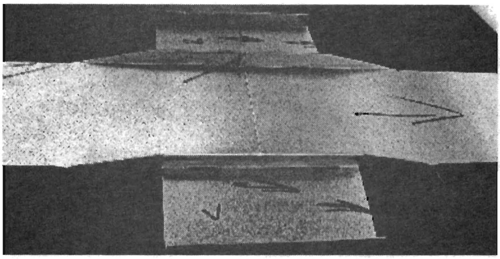

Fig. 13 Tapered lips of middle sections for 0.06-in sheet steel specimen

It was found that the 0.06-in (1.5-mm) sheet specimens failed in the HAZs, as shown in Fig. 14. The failure mechanism is similar to that of the longitudinal flare-bevel welded connection illustrated in Fig. 9, but the longitudinal flare-vee welded connections were subjected to gross deformations as shown in Fig. 15. The 0.12-in (3.0-mm) sheet specimens, on the other hand, failed in the weld metal as shown in Fig. 16. This is also consistent with the longitudinal flare-bevel welded connections in the same sheet steel reported in the preceding section.

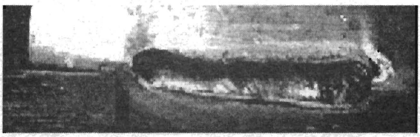

Fig. 14 HAZ failure at the tension end of a flare-vee weld in 0.06-in sheet steel

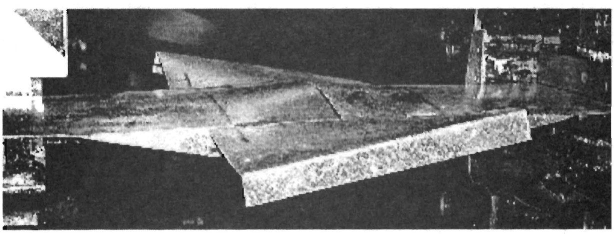

Fig. 15 Gross deformation of 0.06-in specimen

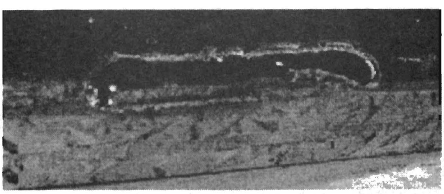

Fig. 16 Weld shear failure of flare-vee welded connection in 0.12-in sheet steel

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 ratio of the ultimate test loads P_t to failure loads P_p (which is twice V_w) are shown in Tables 13 and 14 for the 0.06-in (1.5-mm) and the 0.12-in (3.0-mm) sheet steel specimens, respectively.

Table 13 Longitudinal flare-vee welds in 0.06-in G450 sheet steel, predicted using Equation (2b)

	Average length of failed welds		P_t/P_p
	in	**mm**	
LFVW15.1	0.87	22	0.73
LFVW15.2	1.02	26	0.77
LFVW15.3	1.30	33	0.71
LFVW15.4	1.46	37	0.65
LFVW15.5	1.61	41	0.63

Table 14 Longitudinal flare-vee welds in 0.12-in G450 sheet steel, predicted using Equation (2b)

	Average length of failed welds		P_t / P_p
	in	**mm**	
LFVW30.1	1.22	31	0.59
LFVW30.2	1.65	42	0.59
LFVW30.3	1.93	49	0.60
LFVW30.4	2.01	51	0.62
LFVW30.5	2.44	62	0.59

It is evident from Table 13 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 13, a reliability analysis was carried out. Table 15 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 15 Statistical parameters of longitudinal flare-vee welded connections

	0.06-in	0.12-in
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
ϕ	0.55	0.55
β	2.4-4.0	2.0-3.2

P_m = mean value of P_t/P_p

V_P = coefficient of variation of P_t/P_p

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

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

In the earlier work on longitudinal fillet welded connections (Teh & Hancock 2002), 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 0.06-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 0.06-in (1.5-mm) specimens and the statistical parameters shown in Table 15 that Equation (2b) cannot be used to design flare-vee welded connections in 0.12-in (3.0-mm) G450 sheet steel. The safety indices for the 0.12-in 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 0.12-in sheet steel is associated with shear failure of the weld metal itself rather than the sheet steel, as depicted in Fig. 16.

The failure loads of the longitudinal flare-vee welded connections in 0.12-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), which is based on shear failure of the weld metal,

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

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 0.16 in (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 0.16 in (4 mm), which is a conservative measure as the actual average thickness is slightly less than 0.16 in.

The welding electrode used in the present work was 0.8 mm ES6-GC/M-W503AH, which was manufactured by CIG Weld Autocraft 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 74.2 ksi (512 MPa) even though the nominal tensile strength is 76.1 ksi (525 MPa) (CIGWELD 1993). The value of f_{uw} used in computing the failure loads shown in Table 16 was thus assumed to be 74.2 ksi (512 MPa).

Table 16 Longitudinal flare-vee welds in 0.12-in G450 sheet steel, predicted using Equation (3)

	Average length of failed welds		P_t / P_p
	in	**mm**	
LFVW30.1	1.22	31	1.05
LFVW30.2	1.65	42	1.06
LFVW30.3	1.93	49	1.08
LFVW30.4	2.01	51	1.11
LFVW30.5	2.44	62	1.06

It is evident from Tables 14 and 16 that for longitudinal flare-vee welded connections in 0.12-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 0.12-in sheet steel is due to the fact that the weld throat size of a flare-bevel weld is significantly larger than that of a flare-vee weld. The difference in weld throat size is due mainly to the relatively sharp corners of the channel sections fabricated in the present work.

A separate report (Teh & Hancock 2001b) examines the strength of flare-bevel welded connections in 0.1-in (2.5-mm) DuraGal angle sections, which have a relatively large corner radius.

Fabricators' specimens and macro test

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

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 17 lists the ratios of the ultimate test loads to the nominal failure loads of the fabricators' specimens, the latter computed using the nominal tensile strength of 70 ksi (480 MPa) specified in AS/NZS 4600 (SA/SNZ 1996a). For the purpose of comparison, the average ratios of the in-house specimens reported in Tables 1 and 2 are also included in the table. The connection designations used in Table 17 are consistent with those used in previous sections.

Table 17 Test results of fabricators' specimens (P_t/P_p)

Fabricator	TBWD15	TBWD30	LBWD15	LBWD30
In-house*	1.04	0.94	0.86	0.86
A	0.72	0.81	0.86	0.71
B	0.96	1.06	0.88	0.90
C	0.89	0.74	0.84	0.70
D	0.84	0.76	0.82	0.69

*Average values of specimens tested

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. 17. Note also that all except for the connection in 0.12-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. 17 Flare-bevel weld in 1.5-mm sheet steel produced by Fabricator A

The longitudinal flare-bevel welded connections in 0.06-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. 9. 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, all the longitudinal flare-bevel welded connections in 0.12-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. 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).

Discussions and conclusions

The existing equation specified in Clause 5.2.6.2(a) of AS/NZS 4600 (SA/SNZ 1996a), or Section E2.5(a) of AISI Specification (AISI 1996), 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 0.12-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/NZS 4600 (SA/SNZ 1996a), or Section E2.5(b) of AISI Specification (AISI 1996), 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 0.06-in (1.5-mm) G450 sheet steel. Notwithstanding the present reliability analysis results, the weld capacity of a longitudinal flare-bevel welded connection in 0.12-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/NZS 4600, or Section E2.5(b) of AISI Specification (AISI 1996), to design flare-vee welded connections in 0.06-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 0.12-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.

There appears to be considerable variation in the quality of flare-bevel welded connections in thin sheet steels fabricated in the industry at large. The inferior quality may be caused by non-compliance with the relevant standards and/or the use of certain welding procedures which result in seriously weakened heat affected zones.

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Appendix I – Statistical parameters common to all types of connections

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

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

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

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