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Calibrattions of Cold-Formed Steel Welded Connections

F. M. Tangorra

R. M. Schuster

Roger A. LaBoube
Missouri University of Science and Technology, laboube@mst.edu

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CALIBRATIONS OF COLD-FORMED STEEL WELDED CONNECTIONS

F.M. Tangorra[1], R.M. Schuster[2], and R.A. LaBoube[3]

ABSTRACT

The purpose of this project was to recalibrate the welded connection equations currently contained in the American Iron and Steel Institute (AISI) Specification for the Design of Cold-Formed Steel Structural Members (AISI 1996a). Only one factor of safety of 2.50 is presented for the each of the various types of welded connections when using allowable stress design (ASD), but different respective resistance factors are given for load and resistance factor design (LRFD). The data used was solely taken from the research conducted by Peköz and McGuire (Peköz and McGuire 1979). Calibrations were carried out and based on both the AISI Specification (AISI 1996a) and the Canadian S136 Standard (CSA 1994). The results of this study have already been adopted by both of these cold formed steel design agencies, as well as by the North American Specification for the Design of Cold-Formed Steel Structural Members (NAS 2001).

1.0 INTRODUCTION

In the current AISI Specification for the Design of Cold-Formed Steel Structural Members (AISI 1996a) different resistance factors are given for the various cases of welded connections in Section E2, however, only one factor of safety is given for all of these cases. Having only one factor of safety is not consistent with the different resistance factors. Therefore, a calibration study was initiated to establish the respective factors of safety in conjunction with the different resistance factors. Since the S136 Standard (CSA 1994) committee for Cold Formed Steel Structural Members has recently adopted the current AISI Specification (AISI 1996) welded connection approach as part of the North American Specification (NAS 2001) initiative under the NAFTA umbrella, resistance factor calibrations for the S136 Standard (CSA 1994) were also carried out.

Only the data from Peköz and McGuire (Peköz and McGuire 1979) was used in the calibration of the applicable welded connection equations currently in the AISI Specification (AISI 1996a). The calibration approach used was based on the calibration method given in the Commentary on the AISI Specification (AISI 1996b).

[1] M.A.Sc. Student, Department of Civil Engineering, University of Waterloo, Canada
[2] Professor of Structural Engineering, Department of Civil Engineering, University of Waterloo, Canada
[3] Professor of Civil Engineering, University of Missouri-Rolla, Rolla, Missouri, USA

2.0 CALIBRATION

Resistance factors, ϕ, are used with the LRFD design method in the AISI Specification (AISI 1996a) and the LSD design method in the S136 Standard (CSA 1994). They are determined in conformance with load factors to provide a target reliability index, β, of 3.5 for the AISI Specification (AISI 1996a) provisions and 4.0 for the S136 Standard provisions (CSA 1994).

The general equation for β as presented in the AISI Commentary (AISI, 1996) is as follows:

$$\beta = \frac{\ln\left(R_m / Q_m\right)}{\sqrt{V_R^2 + V_Q^2}} \tag{2.1}$$

Where R_m and Q_m are the mean nominal resistance and load effect, respectively, while V_R and V_Q are the corresponding coefficients of variations. These terms are presented by Equations 2.2 to 2.5 (AISI 1996b).

$$R_m = R_n P_m M_m F_m \tag{2.2}$$

$$Q_m = C(D_m + L_m) \tag{2.3}$$

$$V_R = \sqrt{V_P^2 + V_M^2 + V_F^2} \tag{2.4}$$

$$V_Q = \frac{\sqrt{(D_m V_D)^2 + (L_m V_L)^2}}{D_m + L_m} \tag{2.5}$$

Where: R_n = nominal resistance
P_m = mean ratio of experimental to calculated results
M_m = mean ratio of actual yield point to minimum specified value
F_m = mean ratio of actual to specified section modulus
C = coefficient
D_m = mean dead load intensity (= 1.05 D_n^*)
L_m = mean live load intensity (= L_n^*)
D_n = nominal dead load intensity
L_n = nominal live load intensity
V_P = coefficient of variation of test results
V_M = coefficient of variation of material factor
V_F = coefficient of variation of fabrication factor
V_D = coefficient of variation of the dead load intensities
V_L = coefficient of variation of the live load intensities

*Values recommended by Hsiao et al. (1988)

A satisfactory design can be obtained by equating the factored resistance to the factored loads, as follows:

$$\phi R_n = C(\alpha_D D_n + \alpha_L L_n) \tag{2.6}$$

Where α_D and α_L are the dead and live load factors, respectively, such that the load combinations are

1.2D+1.6L for AISI (AISI 1996a) and
1.25D+1.5L for S136 (CSA 1994).

The dead to live load ratios, D/L, are
1/5 in AISI Specification (AISI 1996a) and
1/3 in S136 (CSA 1994).

By substituting the previous equations into Equation 2.6, the following expressions for ϕ (Beshara 1999) are obtained:

For AISI $$\phi = \frac{1.521(P_m M_m F_m)}{e^{\beta\sqrt{V_R^2+V_Q^2}}} \quad (2.7)$$

For S136 $$\phi = \frac{1.420(P_m M_m F_m)}{e^{\beta\sqrt{V_R^2+V_Q^2}}} \quad (2.8)$$

By using Equation 2.7 for ϕ, the corresponding factor of safety, Ω, can be computed as follows:

For AISI $$\Omega = \frac{1.2 D/L + 1.6}{\phi(D/L + 1)} \quad (2.9)$$

Where all terms have been previously defined.

2.1 Difference between AISI (AISI 1996a) and S136 (CSA 1994)

Since the S136 Commentary (CSA 1995) does not contain any detailed information regarding the development of the resistance factors, it was decided to use the methodology outlined in the AISI Commentary (AISI 1996b). Consequently, the values of M_m, V_M, F_m, and V_F were taken from Table F1 – [Statistical Data for the Determination of Resistance Factor] of the AISI Specification (AISI 1996a). The relevant portions for welded connections of Table F1 are summarised in Table 2.1.

It can be observed from Table 2.1 that the values of M_m, V_M, F_m, and V_F are consistent for each type of weld, with the exception of a plate failure for Arc Spot Welds and Fillet Welds. In that case, V_M and V_F are 0.08 and 0.15 instead of 0.10 and 0.10, respectively. Changing these two values to 0.10 in both cases would not change the calibration results by any appreciable amount.

3.0 Data and Calibration Results

A total of 342 tests were carried out on symmetric fillet, flare bevel, arc spot, and arc seam welded connections subjected to monotonically increasing static loading (Peköz and McGuire 1979). The breakdown of test specimens is summarized in Table 3.1 and the calibration results are presented in detail according to the type of welded connection, as follows. The typical weld failure modes are shown in Figure 1 of the Appendix. For additional detail, consult (Tangorra et al. 2001).

From hereon, all equations refer to those found in the AISI Specifications (AISI 1996a).

Table 2.1 – Statistical Data for Welded Connections and Tearing of Plate Material (AISI 1996a)

Type of Component	M_m	V_M	F_m	V_F
Welded Connections				
Arc Spot Welds				
Shear Strength of Welds	1.10	0.10	1.00	0.10
Plate Failure	1.10	0.08	1.00	0.15
Arc Seam Welds				
Shear Strength of Welds	1.10	0.10	1.00	0.10
Plate Failure	1.10	0.10	1.00	0.10
Fillet Welds				
Shear Strength of Welds	1.10	0.10	1.00	0.10
Plate Failure	1.10	0.08	1.00	0.15
Flare Groove Welds				
Shear Strength of Welds	1.10	0.10	1.00	0.10
Plate Failure	1.10	0.10	1.00	0.10
Tearing of Plate Material				
Plate Failure	1.10	0.10	1.00	0.05

Table 3.1 – Number of Test Specimens Used from (Peköz and McGuire 1979)

Weld Type	Number of Specimens
Arc Spot Welds	124
Arc Seam Welds	23
Longitudinal Fillet Welds	64
Transverse Fillet Welds	55
Transverse Flare-Bevel Welds	42
Longitudinal flare-Bevel Welds	32
Total	**340**

3.1 Arc Spot Welds

In the AISI Specification (AISI 1996a), arc spot welds are divided into two types, i.e., Section E2.2.1 - Shear and Section E2.2.2 - Tension. The data obtained from (Peköz and McGuire 1979), however, only dealt with arc spot welds subjected to shear. Since the design provision of Section E2.2.2 has been revised in the North American Specification, the calibration of that section was not considered in this paper.

The data collected were divided according to the governing failure equation presented in Section E2.2.1-1 of the AISI Specification (AISI 1996a). Failure of 37 specimens was governed by Eq. E2.2.1-1, while 55 specimens by Eq. E2.2.1-2, 12 specimens by Eq. E2.2.1-3, and 11 specimens by Eq. E2.2.1-4. The calibration results are summarised in Tables 3.2 and 3.3.

Table 3.2 – Factors of Safety and Resistance Factors for Arc Spot Welded Connections Governed by Eq. E2.2.1-1 (AISI 1996a)

		Sec. E2.2.1(a) Eq. E2.2.1-1
	No. of specimens (n)	37
	Mean	1.14
	Standard Deviation	0.263
	Coefficient of Variation	0.231
AISI	Ω	2.66
	ϕ	0.577
S136	ϕ	0.476

The 37 specimens used in the calibration of Table 3.2, were identified as having failed in weld shear (Galambos and Yu 1985).

As can be observed in Table 3.2, a factor of safety, Ω, of 2.66 and a resistance factor, ϕ, of 0.577 was obtained for a β value of 3.5 (AISI 1996a), while a resistance factor, ϕ, of 0.476 was obtained for a β value of 4 (CSA 1994).

As shown in Table 3.3 for the 55 specimens whose failure was predicted by Eq. E2.2.1-2, a factor of safety, Ω, of 2.20 and a resistance factor, ϕ, of 0.698 was obtained for a β value of 3.5 (AISI 1996a), while a resistance factor, ϕ, of 0.591 was obtained for a β value of 4 (CSA 1994).

Table 3.3 – Factors of Safety and Resistance Factors for Arc Spot Welded Connections Governed by Eq. E2.2.1-2, Eq. E2.2.1-3, and Eq. E2.2.1-4 (AISI 1996a)

		Sec. E2.2.1(b)		
		Eq. E2.2.1-2	Eq. E2.2.1-3	Eq. E2.2.1-4
	No. of specimens (n)	55	12	11
	Mean	1.2	1	0.999
	Standard Deviation	0.166	0.175	0.221
	Coefficient of Variation	0.139	0.174	0.221
AISI	Ω	2.2	2.79	3.09
	ϕ	0.698	0.549	0.496
S136	ϕ	0.591	0.459	0.408

For the 12 specimens whose failure was predicted by Eq. E2.2.1-3, a factor of safety, Ω, of 2.79 and a resistance factor, ϕ, of 0.549 was obtained for a β value of 3.5 (AISI 1996a), while a resistance factor, ϕ, of 0.459 was obtained for a β value of 4 (CSA 1994).

Finally, for the 11 specimens whose failure was predicted by Eq. E2.2.1-4, a factor of safety, Ω, of 3.09 and a resistance factor, ϕ, of 0.496 was obtained for a β value of 3.5 (AISI 1996a), while a resistance factor, ϕ, of 0.408 was obtained for a β value of 4 (CSA 1994).

It can be observed from Table 3.4, where the current and calculated factors of safety ar resistance factors are being compared using the Commentary of AISI (AISI 1996b), that:

- for Eq. E2.2.1-1 the recommended factor of safety, Ω, is 6.4% greater than the curre value used in the AISI Specification (AISI 1996a) and the recommended resistanc factor, ϕ, is 3.8% less than the current value specified by the AISI Specification (AI 1996a); while the recommended resistance factor, ϕ, for the S136 Standard (CS 1994) is 29% smaller than the current value used.
- for Eq. E2.2.1-2 the recommended factor of safety, Ω, is 12% smaller than the curre value used in the AISI Specification (AISI 1996a) and the recommended resistanc factor, ϕ, is 15% greater than the current value specified by the AISI Specificatio (AISI 1996a); while the recommended resistance factor, ϕ, for the S136 Standa (CSA 1994) is 12% smaller than the current value used.
- for Eq. E2.2.1-3 the recommended factor of safety, Ω, is 12% greater than the curre value used in the AISI Specification (AISI 1996a) and the recommended resistanc factor, ϕ, is 10% greater than the current value specified by AISI Specification (AI 1996a); while the recommended resistance factor, ϕ, for the S136 Standard (CS 1994) is 31% smaller than the current value used.
- for Eq. E2.2.1-4 the recommended factor of safety, Ω, is 24% greater than the curre value used in the AISI Specification (AISI 1996a) and the recommended resistanc factor, ϕ, is 0.8% smaller than the current value specified by AISI Specification (AI 1996a); while the resistance factor, ϕ, for the S136 Standard (CSA 1994) is 39 smaller than the current value used.

Table 3.4 – Comparison Between Current and Calculated Values of Factors of Safety and Resistance Factors for Arc Spot Welded Connections (AISI 1996a)

	AISI				S136	
	Current		Calculated		Current	Calculated
	Ω	ϕ	Ω	ϕ	ϕ	ϕ
Eq. E2.2.1-1	2.50	0.60	2.66	0.577	0.67	0.476
Eq. E2.2.1-2	2.50	0.60	2.20	0.698	0.67	0.591
Eq. E2.2.1-3	2.50	0.50	2.79	0.549	0.67	0.459
Eq. E2.2.1-4	2.50	0.50	3.09	0.496	0.67	0.408

3.2 Arc Seam Welds

A total of 23 specimens were available from (Peköz and McGuire 1985) for this weld type. In the AISI Specification (AISI 1996a), arc seam welds are covered in Section E2.3.

Since only one factor of safety and one resistance factor is given for Arc Seam Welds in the AI Specification (AISI 1996a), the data analysed and summarised in Table 3.5 makes no distinctio between specimens governed by either Eq. E2.3-1 or Eq. E2.3-2.

As can be observed from Table 3.5, a factor of safety, Ω, of 2.47 and a resistance factor, ϕ, of 0.622 was obtained for a β value of 3.5 (AISI 1996a), while a resistance factor, ϕ, of 0.519 was obtained for a β value of 4 (CSA 1994).

Table 3.5 – Factors of Safety and Resistance Factors for Arc Seam Welded Connections Governed by Eq. E2.3-1 or Eq. E2.3-2 (AISI 1996a)

		Sec. E2.3	
		Eq. E2.3.1-1	Current Values
	No. of specimens (n)	23	
	Mean	1.15	
	Standard Deviation	0.234	
	Coefficient of Variation	0.203	
AISI	Ω	2.47	2.50
	ϕ	0.622	0.60
S136	ϕ	0.519	0.67

It can be observed from Table 3.5, where the current and calculated factors of safety and resistance factors are being compared using the AISI Commentary (AISI 1996b), that:

- for Eq. E2.3-1 of Eq. E2.3-2 the recommended factor of safety, Ω, is 1.2% smaller than the current value used in the AISI Specification (AISI 1996a) and the recommended resistance factor, ϕ, is 3.7% greater than the current values specified by AISI (AISI 1996a); while the recommended resistance factor, ϕ, for the S136 Standard (CSA 1994) is 23% smaller than the current value used.

3.3 Longitudinal Fillet Welds

A total of 44 data values were available from (Peköz and McGuire 1979). In the AISI Specification (AISI 1996a), longitudinal fillet welds are covered in Section E2.4 (a).

The data collected were divided according to the governing failure equation presented in Section E2.4 (AISI 1996a). Failure of 30 specimens was governed by Eq. E2.4-1, while 14 specimens by Eq. E2.4-2.

As can be observed from Table 3.6, for the 30 specimens whose failure was predicted by Eq. E2.4-1, a factor of safety, Ω, of 2.59 and a resistance factor, ϕ, of 0.592 was obtained for a β value of 3.5 (AISI 1996a), while a resistance factor, ϕ, of 0.505 was obtained for a β value of 4 (CSA 1994).

While, for the 14 specimens whose failure was predicted by Eq. E2.4-2, a factor of safety, Ω, of 3.31 and a resistance factor, ϕ, of 0.463 was obtained for a β value of 3.5 (AISI 1996a), while a resistance factor, ϕ, of 0.391 was obtained for a β value of 4 (CSA 1994).

It can be observed from Table 3.6, where the current and calculated factors of safety and resistance factors are being compared using the Commentary to the AISI Specification (AISI, 1996b), that:

- for Eq. E2.4-1 the recommended factor of safety, Ω, is 3.6% greater than the curre value used in the AISI Specification (AISI 1996a) and the recommended resistanc factor, ϕ, is 1.3% smaller than the current values specified by the AISI Specificatic (AISI 1996a); while the recommended resistance factor, ϕ, for the S136 Standa (CSA 1994) is 19% smaller than the current value used.
- for Eq. E2.4-2 the recommended factor of safety, Ω, is 32% greater than the curre value used in the AISI Specification_(AISI 1996a) and the recommended resistanc factor, ϕ, is 16% smaller than the current value adopted by the AISI Specificatic (AISI 1996a); while the recommended resistance factor, ϕ, for the S136 Standa (CSA 1994) is 37% smaller than the current value used.

Table 3.6 – Factors of Safety and Resistance Factors for Longitudinal Fillet Welded Connections Governed by Eq. E2.4-1 or Eq. E2.4-2 (AISI 1996a)

		Sec. E2.4(a)			
		Eq. E2.4-1	Current Values	Eq. E2.4-2	Current Values
	No. of specimens (n)	30		14	
	Mean	0.977		0.807	
	Standard Deviation	0.109		0.119	
	Coefficient of Variation	0.112		0.147	
AISI	Ω	2.59	2.50	3.30	2.50
	ϕ	0.592	0.60	0.464	0.55
S136	ϕ	0.505	0.67	0.391	0.67

3.4 Transverse Fillet Welds

A total of 54 specimens were available in this category. In the AISI Specification (AISI 1996a transverse fillet welds are covered in Section E2.4 (b).

It can be observed from Table 3.7, which shows the calibrated results, that a factor of safety, Ω of 2.38 and a resistance factor, ϕ, of 0.643 was obtained for a β value of 3.5 (AISI 1996a), whi a resistance factor, ϕ, of 0.556 was obtained for a β value of 4 (CSA 1994).

Table 3.7 – Factors of Safety and Resistance Factors for Transverse Fillet Welded Connections Governed by Eq. E2.4-3 (AISI 1996a)

		Sec. E2.4(b)	
		Eq. E2.4-3	Current Values
	No. of specimens (n)	54	
	Mean	1.00	
	Standard Deviation	0.109	
	Coefficient of Variation	0.109	
AISI	Ω	2.38	2.50
	ϕ	0.643	0.60
S136	ϕ	0.556	0.67

It can be observed from Table 3.7, where the current and calculated factors of safety an resistance factors are being compared using the AISI Commentary (AISI 1996b), that:

- for Eq. E2.4-3 the recommended factor of safety, Ω, is 64.0% smaller than the current value used in the AISI Specification (AISI 1996a) and the recommended resistance factor, ϕ, is 7.2% greater than the current values adopted by the AISI Specification (AISI 1996a); while the recommended resistance factor, ϕ, for the S136 Standard (CSA 1994) is 17% smaller than the current value used.

3.5 Transverse Flare-Bevel Groove Welds

A total of 42 data values were available from (Peköz and McGuire 1979). In the AISI Specification (AISI 1996a), transverse flare-bevel groove welds are covered in Section E2.5 (a). As can be observed from Table 3.8, a factor of safety, Ω, of 2.60 and a resistance factor, ϕ, of 0.591 was obtained for a β value of 3.5 (AISI 1996a), while a resistance factor, ϕ, of 0.501 was obtained for a β value of 4 (CSA 1994).

Table 3.8 – Factors of Safety and Resistance Factors for Transverse Flare-Bevel Groove Welded Connections Governed by Eq. E2.5-1 (AISI 1996a)

		Sec. E2.5(a)	
		Eq. E2.5-1	Current Values
	No. of specimens (n)	42	
	Mean	1.01	
	Standard Deviation	0.165	
	Coefficient of Variation	0.164	
AISI	Ω	2.60	2.50
	ϕ	0.591	0.55
S136	ϕ	0.501	0.67

It can be observed from Table 3.8, where the current and calculated factors of safety and resistance factors are being compared using the AISI Commentary (AISI 1996b), that:

- for Eq. E2.4-3 the recommended factor of safety, Ω, is 4.0% greater than the current value used in the AISI Specification (AISI 1996a) and the recommended resistance factor, ϕ, is 7.5% greater than the current values adopted by the AISI Specification (AISI 1996a); while the recommended resistance factor, ϕ, for the S136 Standard (CSA 1994) is 25% smaller than the current value used.

3.6 Longitudinal Flare-Bevel Groove Welds

A total of 10 data values were used from (Peköz and McGuire 1979). In the AISI Specification (AISI 1996a), longitudinal flare-bevel groove welds are covered in Section E2.5 (b).

The data obtained from (Peköz and McGuire 1979) fell into category (1) as expressed in Section E2.5 (b) (i.e., $t \leq t_w < 2t$), therefore only Eq. E2.5-2 was used in the computation of the weld strength. In addition, of the original 32 specimens (Peköz and McGuire 1979), only 10 were used as indicated by (Galambos and Yu 1985).

It can be observed from Table 3.9 that a factor of safety, Ω, of 2.71 and a resistance factor, ϕ, of 0.565 was obtained for a β value of 3.5 (AISI 1996a), while a resistance factor, ϕ, of 0.478 was obtained for a β value of 4 (CSA 1994).

Table 3.9 – Factors of Safety and Resistance Factors for Longitudinal Flare-Bevel Groove Welded Connections Governed by Eq. E2.5-2 (AISI 1996a)

		Sec. E2.5(b)	
		Eq. E2.5-2	Current Values
	No. of specimens (n)	10	
	Mean	0.970	
	Standard Deviation	0.163	
	Coefficient of Variation	0.168	
AISI	Ω	2.71	2.50
	ϕ	0.565	0.55
S136	ϕ	0.478	0.67

It can be observed from Table 3.9, where the current and calculated factors of safety and resistance factors are being compared using the AISI Commentary (AISI 1996b), that:

- for Eq. E2.5-2 the recommended factor of safety, Ω, is 8.4% greater than the current value used in the AISI Specification (AISI 1996a) and the recommended resistance factor, ϕ, is 5.8% smaller than the current values adopted by the AISI Specification (AISI 1996a); while the recommended resistance factor, ϕ, for the S136 Standard (CSA 1994) is 29% smaller than the current value used.

4.0 Proposed Factors of Safety and Resistance Factors for Design

The resistance factors, ϕ, summarized in Section 3 were rounded off to the nearest 0.05 values, while the factors of safety, Ω, were recalculated using equation 2.9, to obtain the recommended values summarized in Table 4.1.

Table 4.1 – Proposed Factors of Safety and Resistance Factors for Design

AISI Equations	AISI				S136	
	Ω		ϕ		ϕ	
	Current	Proposed	Current	Proposed	Current	Proposed
Eq. E2.2.1-1	2.50	**2.55**	0.60	**0.60**	0.67	**0.50**
Eq. E2.2.1-2	2.50	**2.20**	0.60	**0.70**	0.67	**0.60**
Eq. E2.2.1-3	2.50	**2.80**	0.50	**0.55**	0.67	**0.45**
Eq. E2.2.1-4	2.50	**3.05**	0.50	**0.50**	0.67	**0.40**
Eq. E2.3-1 or Eq. E2.3-2	2.50	**2.55**	0.60	**0.60**	0.67	**0.50**
Eq. E2.4-1	2.50	**2.55**	0.60	**0.60**	0.67	**0.50**
Eq. E2.4-2	2.50	**3.05**	0.55	**0.50**	0.67	**0.40**
Eq. E2.4-3	2.50	**2.35**	0.60	**0.65**	0.67	**0.60**
Eq. E2.5-1	2.50	**2.55**	0.55	**0.60**	0.67	**0.50**
Eq. E2.5-2	2.50	**2.80**	0.55	**0.55**	0.67	**0.45**

5.0 CONCLUSIONS

Currently in the AISI Specification (AISI 1996a) different resistance factors are given for the various cases of welded connections, however, only one factor of safety is presented for all of these cases. This is not consistent with the variable resistance factors.

Using the data of (Peköz and McGuire 1979), calibrations for factors of safety and resistance factors based on the AISI Specification (AISI 1996a) have been established and are contained in this paper. Similar calibrations were also carried out for the S136 Standard (CSA 1994).

Equations E2.5-3 and E2.5-4 of the AISI Specification (AISI 1996a) were not considered in the calibration exercise since no data was available from (Peköz and McGuire 1979).

Finally, it can be concluded that the calibration of the resistance factors of this study, shows strong agreement with the existing resistance factors of the AISI Specification(AISI 1996a), as developed by (Hsiao et al. 1988) and (Galambos and Yu 1985).

The calibrated results of this study have already been accepted by the North American Specification (NAS 2001) for the design of cold-formed steel structural members.

6.0 ACKNOWLEDGEMENTS

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8.0 APPENDIX – FAILURE MODES

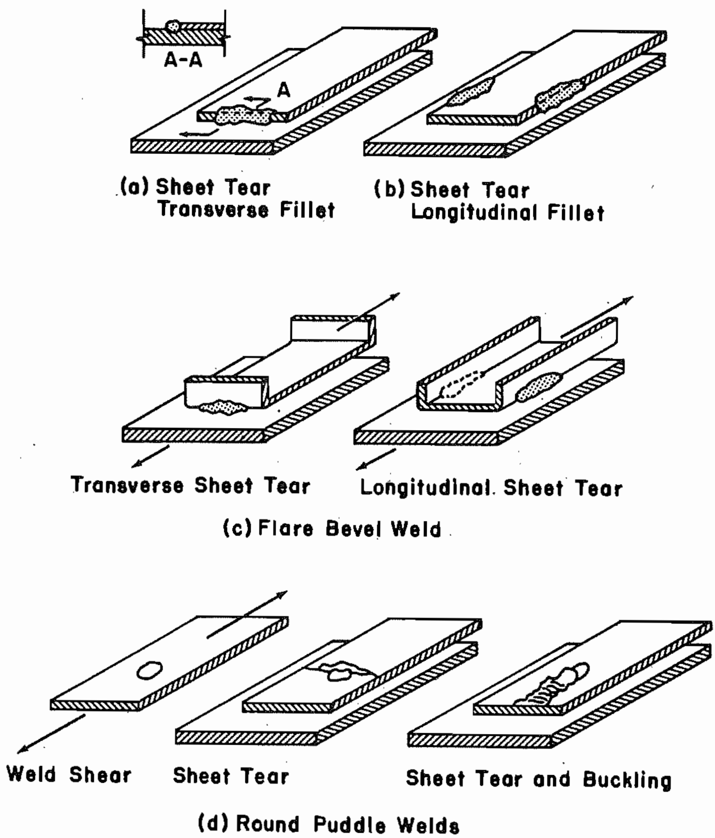

Figure 1 – Typical Failure Modes of Welded Connections [Peköz and McGuire (1979)]