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Abstract

The bearing strength of bolted connections is treated differently in the two current North American Cold-Formed Steel Design documents, the AISI Specification in the USA (AISI 1996a) and the S136 Standard in Canada (CSA 1994). In the case of the S136 Standard (CSA 1994), only one expression is presented that applies to all bolted connections such as single and double shear, as well as, with and without washers. In the AISI Specification (AISI 1996a), however, a distinction is made between single shear and double shear connections and the use of washers.

Contained in this paper are the calibration results of single and double shear cold-formed steel bolted connections with and without washers that failed in bearing. Calibrations were carried out in accordance with the AISI Commentary (AISI 1996b) to establish the resistance factors and respective factor of safety, which have already been adopted by the North American Specification (NAS 2001).

1.0 Introduction

The bearing strength of bolted connections is treated differently in the two current North American Cold-Formed Steel Design documents, the AISI Specification in the USA (AISI 1996a) and the S136 Standard in Canada (CSA 1994). In the case of the S136 Standard (CSA 1994), only one expression is presented that applies to all bolted connections such as single and double shear, as well as, with and without washers. In the AISI Specification (AISI 1996a), however, a distinction is made between single shear and double shear connections and the use of washers.

More specifically, the following two categories are presented, with and without washers:

1) Inside sheet of double shear connection and

2) Single shear and outside sheet of double shear connection.

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The North American Specification for the design of cold-formed steel structural members (NAS 2001) will replace the AISI Specification (AISI 1996a) and the S136 Standard (CSA 1994) and provide a unified design approach for North America.

Contained in this paper are the calibration results of single and double shear cold-formed steel bolted connections with and without washers that failed in bearing. The test data were compared with the AISI Specification (AISI 1996) and the S136 Standard (CSA 1994) methods for determining the bearing strength of a cold-formed steel bolted connection. Comparisons were also made with the method contained in the forthcoming North American Specification for the Design of Cold-Formed Steel Structural Members (NAS 2001), which is expected to be published in June of this year. Calibrations were carried out in accordance with the AISI Commentary (AISI 1996b) to establish the resistance factors and respective factor of safety.

2.0 Bearing Strength Methods

2.1 Current AISI Approach (AISI 1996a)

Section E3.3 of AISI outlines the design approach used to determine the nominal bearing strength. Unlike S136, AISI uses multiple formulations of the nominal bearing strength expressions presented in a tabular format. This format allows the bearing factor to varies from 2.22 to 3.33, recognizing the influence washers have on the bearing strength of a connection. Summarized in Tables 1 and 2 are the AISI design provisions. The AISI method recognises that the use of washers does increase the bearing strength, however, the d/t ratio is not included in the expressions. The equations in Tables 1 and 2 give the nominal bearing strength per bolt.

Table 1: Nominal Bearing Strength for Bolted Connections With Washers Under Both Bolt Head and Nut

Thickness of Connected Part, t in. (mm)	Type of Joint	F_u/F_{sy} ratio of Connected Part	Ω ASD	ϕ LRFD	Nominal Strength, P_n
$0.024 \le t < 0.1875$ $(0.61) \le t < (4.76)$	Inside sheet of double shear connection	≥ 1.08	2.22	0.55	$3.33\ F_u\ d\ t$
		< 1.08	2.22	0.65	$3.00\ F_u\ d\ t$
	Single shear and out-side sheets of double shear connection	No Limit	2.22	0.60	$3.00\ F_u\ d\ t$
$t \ge 3/16$ $t \ge (4.76)$	See AISC ASD or LRFD Specifications				

Table 2: Nominal Bearing Strength for Bolted Connections Without Washers Under Both Bolt Head and Nut, or With Only One Washer

Thickness of Connected Part, t in. (mm)	Type of Joint	F_u/F_{sy} ratio of Connected Part	Ω ASD	ϕ LRFD	Nominal Strength, P_n
$0.036 \le t < 0.1875$ $(0.914) \le t < (4.76)$	Inside sheet of double shear connection	≥ 1.08	2.22	0.65	$3.00\ F_u\ d\ t$
	Single shear and out-side sheets of double shear connection	≥ 1.08	2.22	0.70	$2.22\ F_u\ d\ t$
$t \ge 3/16$ $t \ge (4.76)$	See AISC ASD or LRFD Specifications				

2.2 Current S136 Approach (CSA 1994)

Currently in Canada, the factored bearing resistance per bolt, B_r, is computed in accordance with Clause 7.3.5.1 of S136 (Equation 2.1). No differentiation is made between single and double shear bolted connections, with or without washers. The term, C, is the bearing factor, which is a function of the ratio of the nominal bolt diameter to the uncoated sheet thickness, d/t.

$$B_r = \phi_u\, C\, d\, t\, F_u \qquad (2.1)$$

Although it is recommended that a washer be used at the end of the fastener that is turned, the values of Table 3 also apply if washers are not used. The bearing resistance is independent of whether the thread or shank bears, or if the bolt is pretensioned.

Table 3: Bearing Factor, C

Ratio of fastener diameter to member thickness, d/t	C
$d/t < 10$	3
$10 \le d/t \le 15$	30(t/d)
$d/t > 15$	2

2.3 North American Specification Approach (NAS 2001)

The forthcoming North American Specification (NAS 2001) will supercede the AISI Specification (AISI 1996a) and the S136 Standard (CSA 1994). The method used in the North American Specification (NAS 2001) is similar to the S136 Standard (1994) approach. As with the S136 Standard (CSA 1994) approach, the North American Specification (NAS 2001) method for bearing of bolted connections with washers is based on Equation 2.1. However, a new bearing factor formulation is being used, based on research by (Rogers and Hancock 1998, 1999) and (Wallace et al. 2001a). The bearing factor is a function of the d/t ratio and is dependent on the containment of the bearing material, i.e., with washers, without washers, or inside sheet of a double shear connection. Again, the bearing strength per bolt is defined by Equation 2.1.

For single shear and outside sheets of double shear connections, if washers are used, the bearing factor, C, is determined from Table 4.

Table 4: Bearing Factor, C, for Bolted Connections With Washers

Ratio of fastener diameter to member thickness, d/t	C
$d/t < 10$	3.0
$10 \leq d/t \leq 22$	$4 - 0.1(d/t)$
$d/t > 22$	1.8

If washers are not used, the bearing factor, C, in Table 4 is multiplied by 0.75 to recognize the reduced strength of the connection.

For the inside sheet of a double shear connection, the bearing factor, C, in Table 4 is multiplied by 1.33 to recognize the increased containment of the inside sheet.

3.0 Comparison of the Various Methods

3.1 Comparisons

Summarized in Tables 8, 9, and 10 are the comparisons of the statistical results of the bearing design methods currently used by the AISI Specification (AISI 1996a), the S136 Standard (CSA 1994) and the forthcoming North American Specification (NAS 2001).

3.2 Single Shear and Outside Sheets of Double Shear Connection With Washers

Summarized in Table 5 are the statistical results for single shear and outside sheets of double shear bolted connections with washers.

Table 5: Comparisons of Single Shear and Outside Sheets of Double Shear Bolted Connections With Washers

	Number of Specimens	Average P_t/P_c	Standard Deviation	Factor of Variation
(AISI 1996a)	289	0.879	0.212	0.241
(CSA 1994)	289	1.076	0.219	0.203
(NAS 2001)	289	1.052	0.175	0.167

3.3 Single Shear and Outside Sheets of Double Shear Connection Without Washers

Summarized in Table 6 are the statistical results for single shear and outside sheets of double shear bolted connections without washers.

Table 6: Comparisons of Single Shear and Outside Sheets of Double Shear Bolted Connections Without Washers

	Number of Specimens	Average P_t/P_c	Standard Deviation	Factor of Variation
(AISI 1996a)	123	0.965	0.182	0.188
(CSA 1994)	123	0.783	0.144	0.183
(NAS 2001)	123	1.012	0.153	0.151

3.4 Inside Sheet of Double Shear Connection With or Without Washers

Summarized in Table 7 are the statistical results for inside sheet of double shear bolted connections with or without washers. Note that the NAS requires that the bearing factor values from Table 4 be increased by 33% for this type of connection.

Table 7: Comparisons of Inside Sheet of Double Shear Bolted Connections With or Without Washers

	Number of Specimens	Average P_t/P_c	Standard Deviation	Factor of Variation
(AISI 1996a)	130	1.283	0.254	0.198
(CSA 1994)	130	1.396	0.291	0.208
(NAS 2001)	130	1.001	0.189	0.188

4.0 Calibration

Resistance factors, ϕ, are used with the load and resistance factor design (LRFD) method in the AISI Specification (AISI 1996a) and with the limit states design (LSD) method in the S136 Standard (CSA 1994). They are determined in conformance with the respective load factors to provide a target reliability index, β, value of 3.5 according to the AISI provisions and 4.0 for the S136 provisions. The factor of safety, Ω, is only used with the allowable stress design (ASD) method in the AISI Specification (AISI 1996a). For additional detail, consult (Wallace et al. 2001b).

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

$$\phi R_n = c(\alpha_D D_n + \alpha_L L_n) \tag{4.1}$$

Where R_n is the nominal resistance and α_D and α_L are the dead and live load factors, respectively, such that the load combinations are [1.2D + 1.6L] in the AISI Specification (AISI 1996a) and [1.25D + 1.5L] in the S136 Standard (CSA 1994). The dead to live load ratios, D/L, are 1/5 and 1/3, respectively.

Considering Equation (4.1), it can be shown that the resistance factors, ϕ, can be determined as follows.

For (AISI 1996a):

$$\phi = \frac{1.521(P_m M_m F_m)}{e^{\beta\sqrt{V_R^2+V_Q^2}}} \tag{4.2}$$

For (CSA 1994):

$$\phi = \frac{1.420(P_m M_m F_m)}{e^{\beta\sqrt{V_R^2+V_Q^2}}} \tag{4.3}$$

Where:

$$V_R = \sqrt{V_P^2 + V_M^2 + V_F^2} \tag{4.4}$$

$$V_Q = \frac{\sqrt{(D_m V_D)^2 + (L_m V_L)^2}}{D_m + L_m} \tag{4.5}$$

Since the S136 Commentary (CSA 1995) does not contain a detailed description of the development of how to determine the resistance factors, it was decided to use the methodology outlined in the AISI Commentary (AISI 1996b). Hence, the values of M_m = 1.10, V_M = 0.08, F_m = 1.00, and V_F = 0.05 were taken from Table F1 – [Statistical Data for the Determination of Resistance Factor] of the AISI Specification (AISI 1996a).

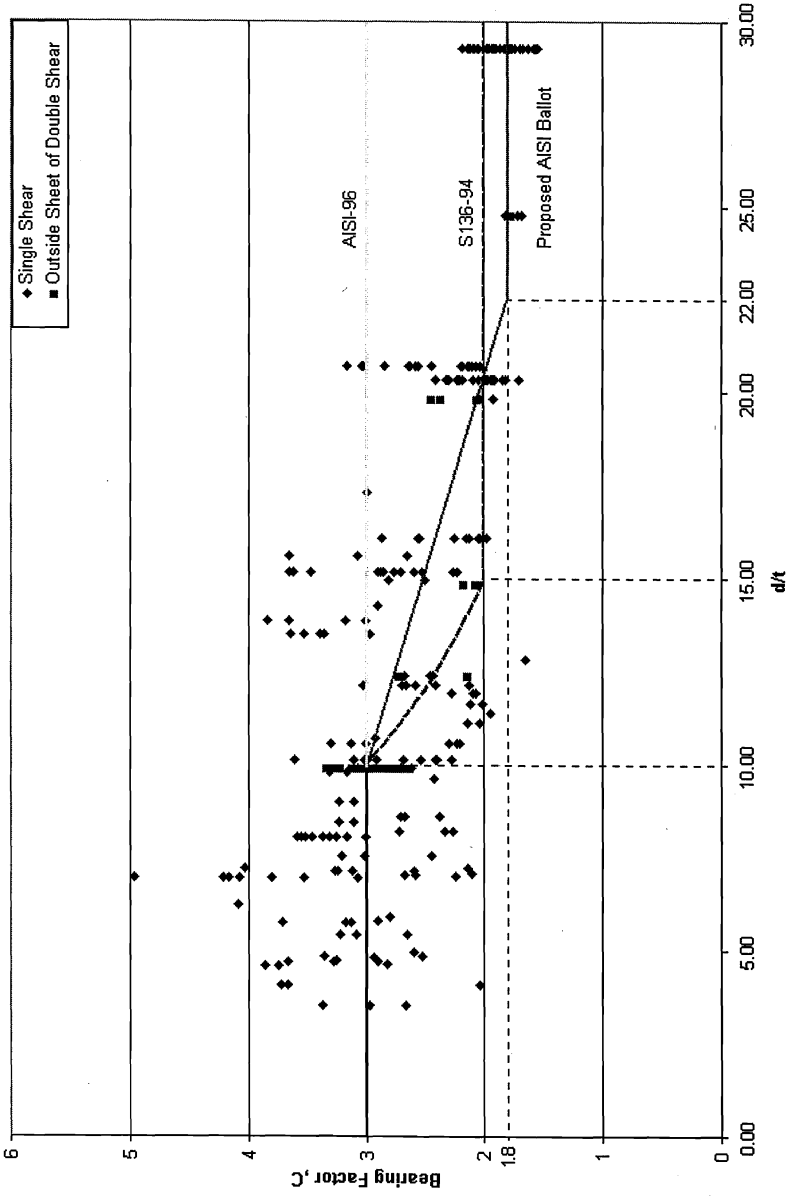

Figure 1: Bearing Factor, C, for Single Shear and Outside Sheets of Double Shear Bolted Connections [With Washers]

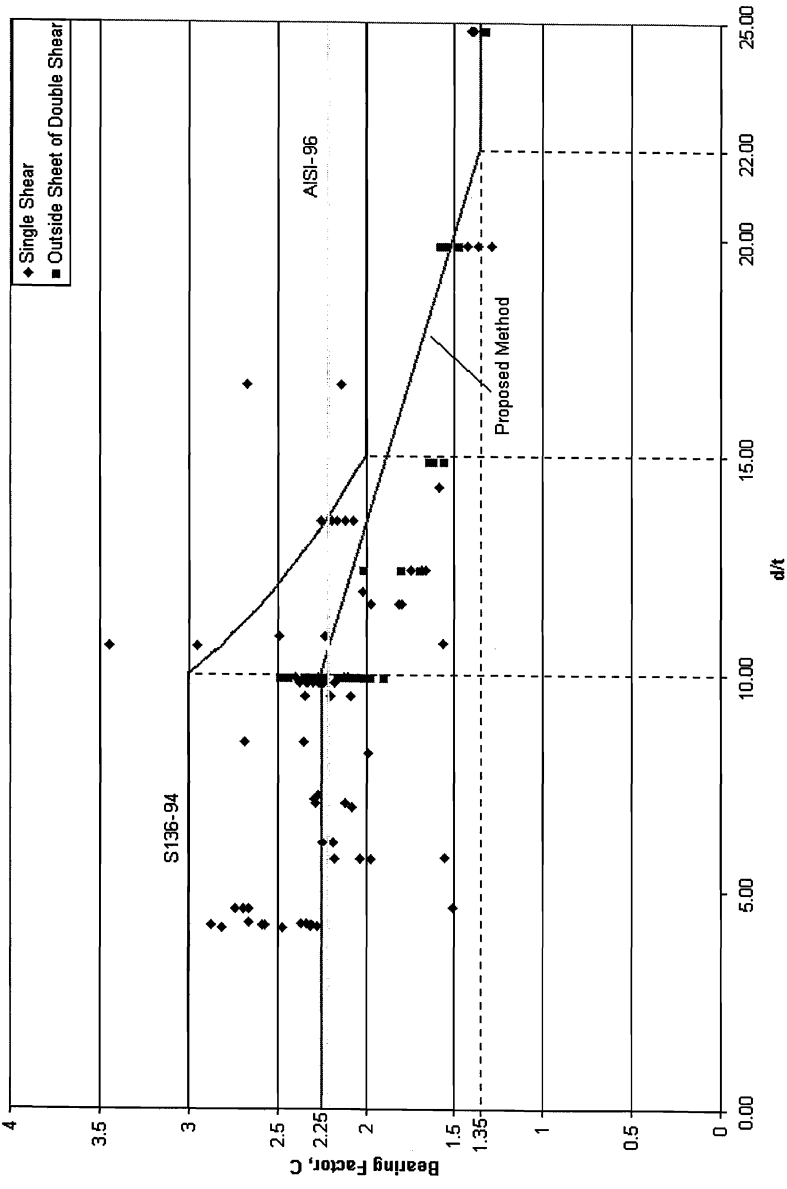

Figure 2: Bearing Factor, C, for Single Shear and Outside Sheets of Double Shear Bolted Connections [Without Washers]

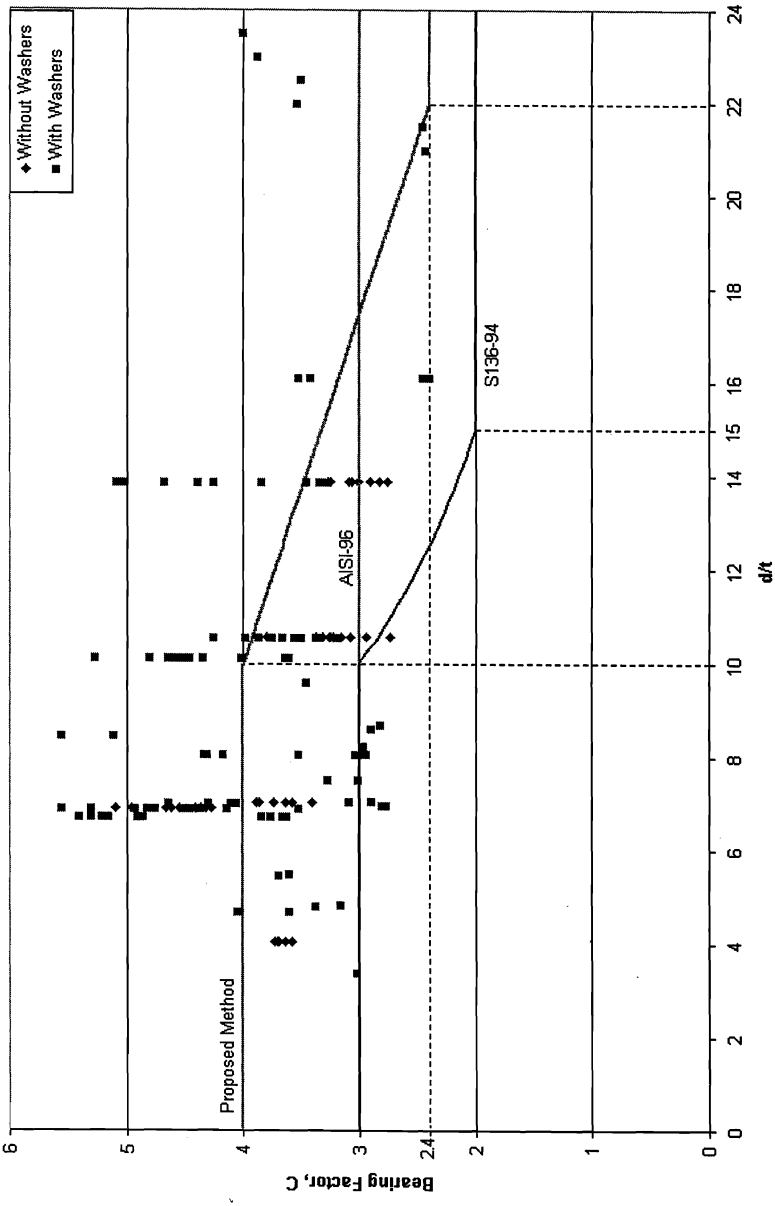

Figure 3: Bearing Factor, C, for Inside Sheet of Double Shear Bolted Connections [With and Without Washers]

By knowing the resistance factor, ϕ, the corresponding factor of safety, Ω, can be computed as follows:

For (AISI 1996a):

$$\Omega = \frac{1.2 D/L + 1.6}{\phi(D/L + 1)} = 1.533/\phi \qquad (4.6)$$

Summarized in Table 8 are the resulting statistical values, the resistance factors, ϕ, and the corresponding factors of safety, Ω, as calculated for the given test data. Statistical comparisons were made between the AISI Specification (AISI 1996a), the S136 Standard (CSA 1994), and the North American Specification (NAS 2001) methods, with and without washers. As can be observed from Table 8, the statistical results are better when using the bearing strength method contained in the North American Specification (NAS 2001).

5.0 Conclusions and Recommendations

The new method for determining the bearing resistance of bolted connections contained in the North American Specification (NAS 2001) provides more consistent results than the methods previously used in the AISI Specification (AISI 1996a) and the S 136 Standard (CSA 1994). Based on the results of this study (Table 8), the resistance factors and factor of safety, rounded to the nearest 0.05, are as contained in the North American Specification (NAS 2001), i.e., reproduced in the Table below.

USA and Mexico		**Canada**
Ω(ASD)	ϕ(LRFD)	ϕ(LSD)
2.50	0.60	0.50

6.0 Acknowledgements

The authors wish to thank the American Iron and Steel Institute for their financial support and sponsorship of this research project. We wish to also thank the Canadian Cold Formed Steel Research Group of the Department of Civil Engineering at the University of Waterloo for having provided valuable resources during the course of the project.

Table 8: Resistance Factors and (AISI 1996a) Factors of Safety for Bolted Connections Failing in Bearing

			Single Shear and Outside Sheets of Double Shear Connection						Inside Sheet of Double Shear Connection With or Without Washers		
			With Washers			Without Washers					
			AISI 1996	S136 1994	NAS 2002	AISI 1996	S136 1994	NAS 2002	AISI 1996	S136 1994	NAS 2002
		Quantity	289	289	289	123	123	123	130	130	130
		Mean	0.879	1.076	1.052	0.965	0.783	1.012	1.283	1.396	1.001
		S.D.	0.212	0.219	0.175	0.182	0.144	0.153	0.254	0.291	0.189
		C.O.V.	0.241	0.203	0.167	0.188	0.183	0.151	0.198	0.208	0.188
		M_m	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
		V_M	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
		F_m	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		P_m	0.879	1.076	1.052	0.965	0.783	1.012	1.283	1.396	1.001
		V_F	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
		m	288	288	288	122	122	122	129	129	129
		C_P	1.01	1.01	1.01	1.02	1.02	1.02	1.02	1.02	1.02
		β (AISI)	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
		D/L (AISI)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
		V_Q (AISI)	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207
		β (S136)	4	4	4	4	4	4	4	4	4
		D/L (S136)	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333
		V_Q (S136)	0.187	0.187	0.187	0.187	0.187	0.187	0.187	0.187	0.187
AISI Commentary	AISI	Ω	3.33	2.48	2.34	2.67	3.25	2.35	2.05	1.93	2.57
		ϕ	0.461	0.619	0.656	0.575	0.472	0.651	0.747	0.794	0.596
	S136	ϕ	0.383	0.523	0.563	0.489	0.402	0.563	0.633	0.670	0.507

7.0 Notations

B_r = factored bearing resistance
C = bearing factor
d = nominal bolt diameter
D_m = mean dead load intensity (= 1.05 D_n^*)
D_n = nominal dead load intensity
F_m = mean ratio of actual to specified section modulus
F_u = tensile strength of sheet
L_m = mean live load intensity (= L_n^*)
L_n = nominal live load intensity
M_m = mean ratio of actual yield point to minimum specified value
P_m = mean ratio of experimental to calculated results
t = uncoated sheet thickness
V_D = coefficient of variation of dead load intensities
V_F = coefficient of variation of fabrication factors
V_L = coefficient of variation of live load intensities
V_M = coefficient of variation of material factors
V_P = coefficient of variation of experimental to calculated results
ϕ = resistance factor
ϕ_u = resistance factor (= 0.75)
Ω = factor of safety (ASD only)

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* Values recommended by (Hsiao et al. 1998)

8.0 References

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