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CALIBRATION OF COLD FORMED STEEL SHEAR EQUATIONS

B. Craig[1] and R.M. Schuster[2]

ABSTRACT

There is a difference in the shear design criteria between the Canadian cold formed steel design Standard, CSA S136-94 (from here on referred to as S136) and the American Iron and Steel Institute Specification for the design of cold formed steel structures, AISI-96 (from here on referred to as AISI). The focus of this paper was to carry out the appropriate calibrations for the factor of safety, Ω, and the resistance factor, ϕ, using the current design approaches of both countries. In the case of the S136 Standard, only the resistance factor was determined. It was assumed at the outset that the nominal shear expressions should not produce an inconsistency on the shear curve.

Using 34 test values from the literature, calibrations were carried out using combinations of S136 and AISI reliability indices, calibration coefficients and shear equations. It was found that using a reliability index of 2.5 and the entire sample size, the existing resistance factor of 0.9 was acceptable in the AISI Specification. This conflicts with the current use of a resistance factor of 1.0 for shear yielding in the AISI Specification. Since S136 uses a reliability index of 3.0, the current resistance factor of 0.9 is unconservative. Examining resistance factors for individual failure modes showed areas where the documents are unconservative.

Additional calibrations were performed on a proposed consistent set of shear equations. Using a reliability index, β, of 2.5 and the dead and live load factors specified by AISI , a resistance factor of 0.95 and a corresponding factor of safety of 1.62 was determined. With a reliability index, β, of 3.0 and the dead and live load factors specified by S136, a resistance factor of 0.85 was established. It is recommended that the proposed shear expressions be used in the current design documents since they provide a smooth transition between failure modes, as well as a more reliable resistance factor and corresponding factor of safety.

1 INTRODUCTION

Cold formed steel has been gaining popularity in the building industry since the early 1940's [1]. Its popularity can be attributed to many factors, including its strength to weight ratio, ease of manufacturing, ease of production, ability to be formed into unique shapes and ease of installation [2]. Due to the wide use of cold formed steel, it is important that design guidelines are easy to understand while providing safe designs. The ultimate goal in North America is to have one unified cold formed steel design document for Canada, the United States, and Mexico.

The focus of this paper was to evaluate the existing shear design expressions of both the Canadian and the American cold formed steel design documents. By examining the current shear design expressions in the S136 Standard [4] and the AISI Specification [5] for the design of cold formed steel structures and re-calibrating resistance factors and factor of safety for web shear, this paper intends to present recommendations towards unification of the two standards.

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2 SHEAR EQUATIONS

The shear resistance of a member is dependent on the web slenderness, the aspect ratio, the material properties and the support conditions [1]. In general, when the web slenderness ratio ($H = h/t$) increases, the shear resistance of the member decreases.

The behavior of the web element can be subdivided into three categories. Members with a small web slenderness ratio, H, typically fail due to shear yielding. Moderate H values result in an inelastic shear buckling failure and large H values indicate failure by elastic shear buckling.

Both S136[4] and AISI[5] have similar requirements in the elastic and inelastic shear buckling regions shown in Appendix A & B, respectively. The differences are in the boundaries between regions and the rounding of coefficients. The principal difference between the two design documents lies in the calculation of shear yielding. In S136[4] a maximum value of $0.64F_y$ is used, while in AISI[5], a value of $0.6F_y$ is being used.

2.1 Existing CSA S136-94 Shear Equations

Reproduced in Appendix A are the current shear expressions used by S136[4]. Shear yielding failure is based on the Von Mises yield theory shown in Eq. 2.1.

$$\tau = {F_y}/{\sqrt{3}} = 0.58F_y \qquad (2.1)$$

This value is further increased by ten percent to an upper limit of 0.64 since the failure will be a gross section failure and therefore not of a catastrophic nature. In addition, the deformations will result in work-hardening and strengthening of the material [3]. Stress calculation for other failure modes is based on shear failure studies [3]. The factored shear resistance of a web element can be calculated by using Eq. 2.2.

$$V_r = \phi A_w F_v \qquad (2.2)$$

In Eq. 2.2, F_v is the nominal shear stress in the web element, A_w is the area of the web and ϕ is the calibrated resistance factor of 0.9 [4]. The graph of the normalized nominal shear stress versus the normalized web slenderness for S136 exhibits a slight inconsistency in the transition between the shear yielding region and the inelastic shear buckling region (Figure 1).

2.2 Existing AISI-96 Shear Equations

The shear equations currently used in the AISI Specification are presented in Appendix B. Similar to S136, shear yielding failure is based on the Von Mises yield theory with a slight increase in strength [5]. The expressions and boundaries have been adjusted in AISI in order to create a smooth transition curve for allowable shear stress versus web slenderness. In the shear yielding region, a resistance factor, ϕ, of 1.0 and a factor of safety, Ω, of 1.50 are being used. In the other regions of the shear curve, a resistance factor of 0.9 and a factor of safety of 1.67 are being used. This creates an inconsistency when plotting nominal shear stress versus web slenderness (Figure 2). The allowable stress plot flows smoothly between regions, however, due to the resistance factor of unity, an increase in the nominal shear resistance occurs between the shear yielding and the inelastic shear buckling region. This change in ϕ and Ω factors causing the inconsistencies in nominal shear resistance, needs to be corrected since this behavior does not model the actual shear stress. However, at the design load level, the AISI Specification is consistent.

2.3 Proposed Shear Equations

Alterations were made to the shear equation in the shear yielding region, to the inelastic shear buckling region and to the corresponding boundary conditions. The major change occurred in the shear yielding region where the maximum value was set equal to 0.6. Presented in Appendix C are the proposed equations in the standard format for the AISI Specification.

The maximum value of the shear yielding region is similar to that presently used by AISI with a change in resistance factor. The equation for the inelastic region and the boundaries have been modified to provide a smooth transition between failure modes (Figure 3). This also provides a more realistic model for the failure behaviour.

Based on the calibration results of this study, a ϕ and Ω factor of 0.95 and 1.62, respectively, is recommended for the AISI Specification. A ϕ factor of 0.85 is recommended for the S136 Standard.

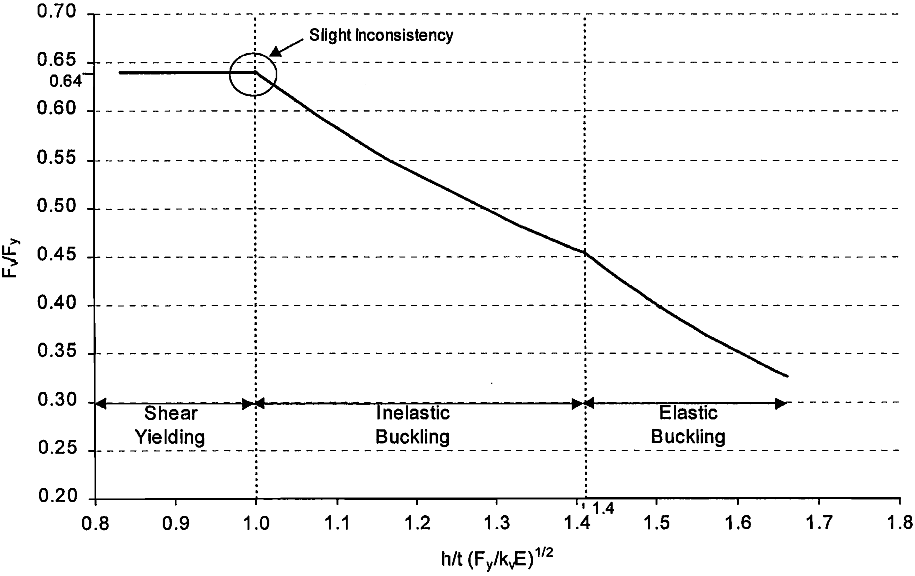


Figure 1: Nominal Shear Stress, CSA 136-94[4]

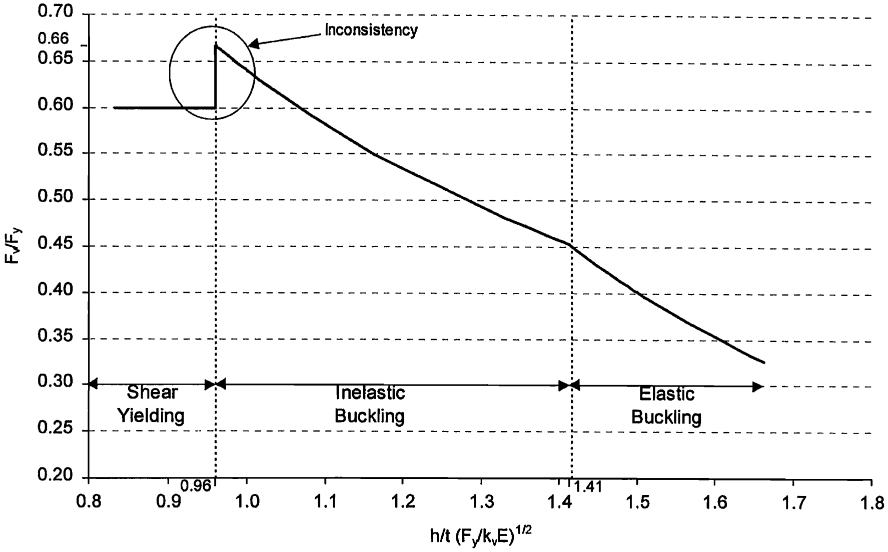


Figure 2: Nominal Shear Stress, AISI-96

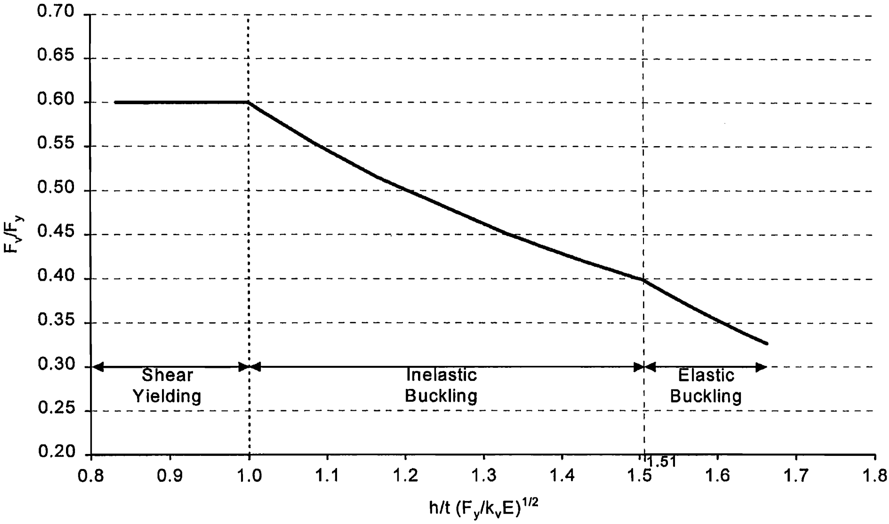
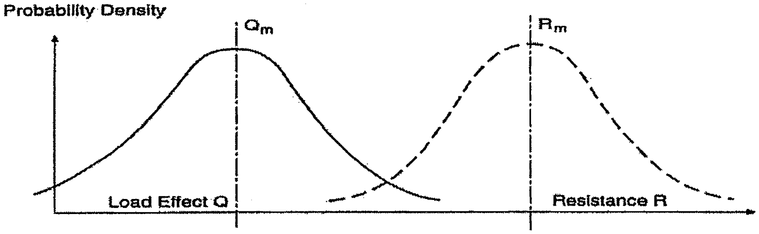


Figure 3: Proposed Nominal Shear Stress

3 CALIBRATION

Using the 34 test values[1], calibrations of the shear equations were carried out to determine the resistance factors, ϕ, and the factors of safety, Ω, for the assumed loading and reliability index, β, values.

The reliability index represents the amount of overlap between the graphs of nominal loading (Q) and nominal resistance (R) (Figure 4). Larger β values represent a smaller overlap between the graphs resulting in a larger region of safety [6].



Definition of the Randomness Q and R

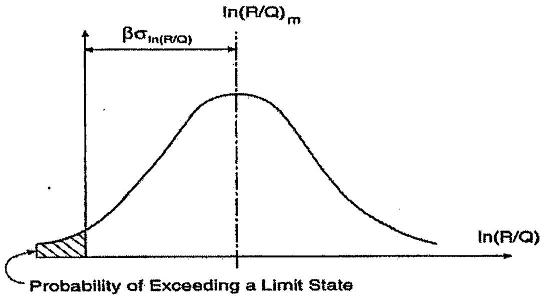


Figure 4: Definition of Reliability Index (β) [6]

The lower bound target β value for members set by the AISI is 2.5 [6]. In the S136 Commentary [3], a range of β values between 3 and 4 is presented. In this study, a β value of 3 for members was assumed. The expression for β is provided in Eq. 3.1 [7].

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

The variables R_m and Q_m represent the mean nominal resistance and loading, respectively. V_R and V_Q represent the coefficients of variation for R and Q, respectively. Each term can be represented by Eq. 3.2 to 3.5 [7].

$$R_m = R_n M_m F_m P_m \tag{3.2}$$

$$Q_m = c(D_m + L_m) \tag{3.3}$$

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

$$V_Q = \frac{\sqrt{(D_m V_D)^2 + (L_m V_L)^2}}{D_m + L_m} \tag{3.5}$$

Where R_n = nominal resistance

P_m = mean ratio of experimental to calculated results

M_m = mean ratio of actual to minimum specified yield point (= 1.10*)

F_m = mean ratio of actual to specified section modulus (= 1.00*)

c = loading coefficient

D_m = mean dead load intensity (= $1.05D_n$**)

L_m = mean live load intensity (=$1.00L_n$**)

D_n, L_n = nominal dead and live load intensities

V_p = coefficient of variation of experimental to calculated results

V_M = coefficient of variation reflecting uncertainties in material properties (= 0.10*)

V_F = coefficient of variation reflection geometric uncertainties (= 0.05*)

V_D, V_L = coefficient of variation of dead and live load intensities (= 0.10**, 0.25**, respectively)

* Values obtained from AISI Specification [5]

** Values obtained from Hsiao [8]

Load and Resistance Factored Design (LRFD), also know as Limit States Design (LSD) in Canada, states that the factored load must be less than or equal to the factored resistance.

$$\sum \gamma_i Q_i \leq \phi R_n \tag{3.6}$$

Where γ and ϕ are load and resistance factors, respectively. Q_i represents the load effects and R_n is the nominal resistance. Equation 3.6 can further be written as the following [6]:

$$\phi R_n = c(\alpha_D D_n + \alpha_L L_n) \tag{3.7}$$

Where α_D and α_L are the dead and live load factors, respectively. A dead load factor of 1.25 and a live load factor of 1.5 is specified in S136. In the calibrations, a dead to live load ratio of 1/3 was used [3]. AISI differs from S136 in that the dead and live load factors are 1.2 and 1.6, respectively. The AISI dead to live load ratio used in the calibration was 1/5 [6]. Table 1 provides a summary of the calibration parameters used in this study.

Table 1: Calibration Parameters

Parameter	AISI-96	CSA S136-94
β	2.5	3.0
α_D	1.2	1.25
α_L	1.6	1.5
D/L	1/5	1/3

By making the appropriate substitutions, expressions for the resistance factors can be obtained, as follows.

For S136
$$\phi = \frac{1.562\,P_m}{e^{\beta\sqrt{0.0475+V_P^2}}} \qquad (3.8)$$

For AISI
$$\phi = \frac{1.673\,P_m}{e^{\beta\sqrt{0.0553+V_P^2}}} \qquad (3.9)$$

The values of P_m and V_p were derived from comparing experimental test values and theoretical failure values. Eq. 3.8 and 3.9 were then used to determine the appropriate ϕ values for the given shear expression. In the case of the AISI Specification[5], allowable stress design (ASD) a similar procedure is used to calculate the factor of safety, Ω. Eq. 3.7 is replaced with Eq. 3.10, which reflects the use of Ω.

$$R_n = \Omega c(D_n + L_n) \qquad (3.10)$$

Rearranging the equations and making the appropriate substitution provides the calibration equation for determining the factor of safety as seen in Eq. 3.11.

For AISI
$$\Omega = \frac{e^{\beta\sqrt{0.0554+V_P^2}}}{1.091P_m} \qquad (3.11)$$

For a more in depth derivation of the calibration expressions, refer to Beshara, 1999 [2].

4 TEST DATA

A total of 34 test data were used in the shear calibration process of this study [1]. Four of these were considered to have failed by shear yielding, eight failed in the inelastic shear buckling region and the remaining 22 failed by elastic shear buckling. It is important to note that it is difficult for members in bending to fail in pure shear without having a stiffened web. Different test setups were used to investigate the effects of reinforced flanges, different connection patterns, various material properties, dimensions and aspect ratios [1]. In-depth testing procedures may be obtained from LaBoube, 1978 [1].

Summarized in Tables 2 to 5 are the experimental and calculated shear resistances for the two documents (S136 and AISI) and the proposed method. Comparisons between tested and calculated values are also presented in Tables 2 to 5, along with their mean and standard deviations.

Table 2: Shear Data Comparison, All Data

Beam	(V_u)test	CSA S136-94			AISI-96			Proposed		
Specimen No.	(kN)	CASE*	V_n (kN)	test/calc	CASE*	V_n (kN)	test/calc	CASE*	V_n (kN)	test/calc
S-1-1	38.21	1	40.60	0.94	1	38.07	1.00	1	38.07	1.00
S-1-2	38.34	1	40.35	0.95	1	37.83	1.01	1	37.83	1.01
S-2-1	34.43	2	36.58	0.94	2	36.53	0.94	2	34.24	1.01
S-2-2	34.79	2	37.37	0.93	2	37.32	0.93	2	34.98	0.99
S-3-1	35.59	3	31.46	1.13	3	31.46	1.13	3	31.46	1.13
S-3-2	37.59	3	31.37	1.20	3	31.37	1.20	3	31.37	1.20
S-8-1	33.36	2	36.40	0.92	2	36.35	0.92	2	34.07	0.98
S-8-2	33.72	2	36.19	0.93	2	36.14	0.93	2	33.88	1.00
S-9-1	33.76	3	30.98	1.09	3	30.98	1.09	3	30.98	1.09
S-9-2	37.37	3	30.99	1.21	3	30.99	1.21	3	30.99	1.21
S-9-4	34.16	3	31.75	1.08	3	31.75	1.08	3	31.75	1.08
S-9-5	31.76	3	31.81	1.00	3	31.81	1.00	3	31.81	1.00
S-9-6	36.70	3	32.57	1.13	3	32.57	1.13	3	32.57	1.13
S-9-7	25.84	3	19.08	1.35	3	19.08	1.35	3	19.08	1.35
S-9-8	27.13	3	18.94	1.43	3	18.94	1.43	3	18.94	1.43
S-10-4	50.71	1	58.19	0.87	1	54.55	0.93	1	54.55	0.93
S-10-5	49.78	1	58.41	0.85	1	54.76	0.91	1	54.76	0.91
S-11-1	51.15	3	48.05	1.06	3	48.05	1.06	3	48.05	1.06
S-11-2	57.69	3	48.18	1.20	3	48.18	1.20	3	48.18	1.20
S-11-3	54.67	3	49.61	1.10	3	49.61	1.10	3	49.61	1.10
S-12-2	47.77	3	38.11	1.25	3	38.11	1.25	3	38.11	1.25
S-12-3	41.19	3	41.22	1.00	3	41.22	1.00	3	41.22	1.00
S-17-1	54.71	3	49.41	1.11	3	49.41	1.11	3	49.41	1.11
S-17-2	53.38	3	49.89	1.07	3	49.89	1.07	3	49.89	1.07
S-18-1	53.60	3	41.68	1.29	3	41.68	1.29	3	41.68	1.29
S-18-2	48.71	3	41.16	1.18	3	41.16	1.18	3	41.16	1.18
S-19-3	36.83	3	26.09	1.41	3	26.09	1.41	3	26.09	1.41
S-20-3	30.92	3	20.35	1.52	3	20.35	1.52	3	20.35	1.52
MS-2-1	35.01	2	36.27	0.97	2	36.21	0.97	2	33.95	1.03
MS-2-2	35.54	2	35.60	1.00	2	35.55	1.00	2	33.32	1.07
MS-3-1	35.05	3	31.64	1.11	3	31.64	1.11	3	31.64	1.11
MS-3-2	32.96	3	31.59	1.04	3	31.59	1.04	3	31.59	1.04
MS-8-1	36.08	2	36.39	0.99	2	36.33	0.99	2	34.06	1.06
MS-8-2	32.47	2	37.12	0.87	2	37.06	0.88	2	34.75	0.93
Number of specimens			n =	34		n =	34		n =	34
Mean			P_m =	1.09		P_m =	1.10		P_m =	1.11
Coefficient of Variation			V_p =	0.1544		V_p =	0.1466		V_p =	0.1333

*Case 1: Shear Yielding
Case 2: Inelastic Shear Buckling
Case 3: Elastic Shear Buckling

Table 3: Shear Data Comparison, Case 1 - Shear Yielding

Beam	(V_u)test	CSA S136-94			AISI-96			Proposed		
Specimen No.	(kN)	CASE*	V_n (kN)	test/calc	CASE*	V_n (kN)	test/calc	CASE*	V_n (kN)	test/calc
S-1-1	38.21	1	40.60	0.94	1	38.07	1.00	1	38.07	1.00
S-1-2	38.34	1	40.35	0.95	1	37.83	1.01	1	37.83	1.01
S-10-4	50.71	1	58.19	0.87	1	54.55	0.93	1	54.55	0.93
S-10-5	49.78	1	58.41	0.85	1	54.76	0.91	1	54.76	0.91
Number of specimens			n =	4		n =	4		n =	4
Mean			P_m =	0.90		P_m =	0.96		P_m =	0.96
Coefficient of Variation			V_p =	0.0544		V_p =	0.0544		V_p =	0.0544

Table 4: Shear Data Comparison, Case 2 - Inelastic Shear Buckling

Beam	(V_u)test	CSA S136-94			AISI-96			Proposed		
Specimen No.	(kN)	CASE*	V_n (kN)	test/calc	CASE*	V_n (kN)	test/calc	CASE*	V_n (kN)	test/calc
S-2-1	34.43	2	36.58	0.94	2	36.53	0.94	2	34.24	1.01
S-2-2	34.79	2	37.37	0.93	2	37.32	0.93	2	34.98	0.99
S-8-1	33.36	2	36.40	0.92	2	36.35	0.92	2	34.07	0.98
S-8-2	33.72	2	36.19	0.93	2	36.14	0.93	2	33.88	1.00
MS-2-1	35.01	2	36.27	0.97	2	36.21	0.97	2	33.95	1.03
MS-2-2	35.54	2	35.60	1.00	2	35.55	1.00	2	33.32	1.07
MS-8-1	36.08	2	36.39	0.99	2	36.33	0.99	2	34.06	1.06
MS-8-2	32.47	2	37.12	0.87	2	37.06	0.88	2	34.75	0.93
Number of specimens			n =	8		n =	8		n =	8
Mean			P_m =	0.94		P_m =	0.95		P_m =	1.01
Coefficient of Variation			V_p =	0.0430		V_p =	0.0430		V_p =	0.0430

Table 5: Shear Data Comparison, Case 3 - Elastic Shear Buckling

Beam	(V_u)test	CSA S136-94			AISI-96			Proposed		
Specimen No.	(kN)	CASE*	V_n (kN)	test/calc	CASE*	V_n (kN)	test/calc	CASE*	V_n (kN)	test/calc
S-3-1	35.59	3	31.46	1.13	3	31.46	1.13	3	31.46	1.13
S-3-2	37.59	3	31.37	1.20	3	31.37	1.20	3	31.37	1.20
S-9-1	33.76	3	30.98	1.09	3	30.98	1.09	3	30.98	1.09
S-9-2	37.37	3	30.99	1.21	3	30.99	1.21	3	30.99	1.21
S-9-4	34.16	3	31.75	1.08	3	31.75	1.08	3	31.75	1.08
S-9-5	31.76	3	31.81	1.00	3	31.81	1.00	3	31.81	1.00
S-9-6	36.70	3	32.57	1.13	3	32.57	1.13	3	32.57	1.13
S-9-7	25.84	3	19.08	1.35	3	19.08	1.35	3	19.08	1.35
S-9-8	27.13	3	18.94	1.43	3	18.94	1.43	3	18.94	1.43
S-11-1	51.15	3	48.05	1.06	3	48.05	1.06	3	48.05	1.06
S-11-2	57.69	3	48.18	1.20	3	48.18	1.20	3	48.18	1.20
S-11-3	54.67	3	49.61	1.10	3	49.61	1.10	3	49.61	1.10
S-12-2	47.77	3	38.11	1.25	3	38.11	1.25	3	38.11	1.25
S-12-3	41.19	3	41.22	1.00	3	41.22	1.00	3	41.22	1.00
S-17-1	54.71	3	49.41	1.11	3	49.41	1.11	3	49.41	1.11
S-17-2	53.38	3	49.89	1.07	3	49.89	1.07	3	49.89	1.07
S-18-1	53.60	3	41.68	1.29	3	41.68	1.29	3	41.68	1.29
S-18-2	48.71	3	41.16	1.18	3	41.16	1.18	3	41.16	1.18
S-19-3	36.83	3	26.09	1.41	3	26.09	1.41	3	26.09	1.41
S-20-3	30.92	3	20.35	1.52	3	20.35	1.52	3	20.35	1.52
MS-3-1	35.05	3	31.64	1.11	3	31.64	1.11	3	31.64	1.11
MS-3-2	32.96	3	31.59	1.04	3	31.59	1.04	3	31.59	1.04
Number of specimens			n =	22		n =	22		n =	22
Mean			P_m =	1.18		P_m =	1.18		P_m =	1.18
Coefficient of Variation			V_p =	0.1215		V_p =	0.1215		V_p =	0.1215

*Case 1: Shear Yielding
Case 2: Inelastic Shear Buckling
Case 3: Elastic Shear Buckling

5 RESULTS

In order to obtain a true comparison between the AISI and S136 documents, eight calibrations were performed. Using a β value of 2.5, four calibration sets were carried out. In the first two calibration sets, the AISI calibration method was used for the calibration of the resistance factor, ϕ, with the corresponding experimental and theoretical values from either document (S136 and AISI). The next two calibration sets were similar except, the S136 calibration method was used. These four calibration sets were repeated using the S136 suggested β value of 3.0. An additional four calibration sets were performed for the proposed expressions to obtain the new resistance factors. Two calibration sets were performed using a target β value of 2.5, the first of which was performed using the AISI calibration method and the other using the S136 calibration method. The calibrations were repeated using a target β value of 3.0. All calibrations were carried out using the complete sample size as well as individual failure regions, the results of which are summarized in Table 6.

Table 6: Calculated Resistance Factor (ϕ) Based on Calibration

Document	Calibration	All Data		Shear Yielding		Inelastic Buckling		Elastic Buckling	
Equation	Method	β=2.5	β=3.0	β=2.5	β=3.0	β=2.5	β=3.0	β=2.5	β=3.0
S136-94	S136-94	0.88	0.77	0.81	0.72	0.85	0.76	0.99	0.87
S136-94	AISI-96	0.90	0.79	0.83	0.73	0.87	0.77	1.02	0.89
AISI-96	S136-94	0.89	0.78	0.86	0.77	0.85	0.76	0.99	0.87
AISI-96	AISI-96	0.92	0.80	0.88	0.78	0.87	0.77	1.02	0.89
Proposed	**S136-94**	**0.92**	**0.81**	**0.86**	**0.77**	**0.90**	**0.81**	**0.99**	**0.87**
Proposed	**AISI-96**	**0.95**	**0.83**	**0.88**	**0.78**	**0.93**	**0.82**	**1.02**	**0.89**

As expected, in all calibration sets, the β value of 3 resulted in lower ϕ factors. When the total sample set was calibrated, a ϕ factor of 0.9 was obtained with a β value of 2.5. This is consistent with the currently used ϕ factors. The assumed β value of 3 resulted in an unconservative value of ϕ = 0.79. These results suggest that the S136 may have used a lower β value in the original calibration of the equations. The use of ϕ equal to 0.9 however, does not agree with the ϕ factor of 1.0 used in the AISI Specification for shear yielding.

When the calibration sets were performed on smaller sample sizes representing the 3 different failure modes, the ϕ factors varied considerably. In the case of elastic and inelastic buckling, all four combinations of equations and test results show similar ϕ factors since the two documents (S136 and AISI) do not differ much in this region. The ϕ factor obtained for elastic buckling with a target β value of 2.5 was larger than that currently used and therefore is on the conservative side. Using a target β value of 3, produced unconservative results. Inelastic buckling showed unconservative values for both β values of 2.5 and 3. The proposed equations produced similar results for the elastic buckling range. The modified inelastic equation produced favorable results by increasing the ϕ factor to a less unconservative value. Using a β value of 2.5, the proposed ϕ value of 0.95 closely agrees with values for inelastic buckling and is conservative for inelastic buckling.

It is observed that the most unconservative use of ϕ values lies within the shear yielding region. Using the AISI equations and a β value of 2.5, a ϕ factor of 0.88 was calculated, which is unconservative compared to the current ϕ of 1.0. Similar problems result with the S136 Standard using a β value of 3. The ϕ factor in this case is 0.72, in comparison to the currently used value of 0.9. In all combinations of equations, calibration coefficients and β values, all answers were unconservative when compared to the current two design document (S136 and AISI) values.

The proposed equations resulted in similar ϕ factors to the AISI calibration results. However, with the proposed ϕ factor of 0.95, the results are more reliable. Members rarely fail in this region, therefore, it is acceptable to be slightly unconservative.

Similar calibrations were carried out based on the ASD method of AISI to verify the current factor of safety, Ω. The results of this calibration are presented in Table 7. Straight comparisons between the Ω values show that the proposed equations provide a more reliable safety factor. The effects are similar to those previously discussed for the resistance factors,ϕ.

Table 7: Calculated Factor of Safety (Ω) Based on Calibration - β = 2.5

Specification Equation	Calibration Method	All Data	Shear Yielding	Inelastic Buckling	Elastic Buckling
AISI-96	AISI-96	1.67	1.74	1.77	1.51
Proposed	**AISI-96**	**1.62**	**1.74**	**1.65**	**1.51**

6 CONCLUSIONS AND RECOMMENDATIONS

The results varied for the different calibrations performed in this study, demonstrating inconsistencies in Specification values. When calibrating the total sample population, the ϕ value of 0.9 is acceptable at a β value of 2.5 in both Standards. This leads to a concern regarding the use of a ϕ value of 1.0 for shear yielding in the AISI Specification. The ϕ factor of 1.0 used by the AISI Specification also creates inconsistencies in the transition between nominal shear yielding failure and nominal inelastic shear buckling failure. By adjusting the Specification equations, ϕ factors and boundary conditions between equations, the proposed equations were able to eliminate the inconstancies and provide a more reliable solution.

It is recommended that the S136[4] Standard use a more well-defined β value in order to obtain the corresponding calibrated ϕ values. Based on the calibrations of this study, a β value of 3 results in a lower ϕ value than desired. Having a predefined β value would remove the concern of using an incorrect ϕ value.

Analyzing individual equations for different failure modes resulted in varying ϕ factors. It was shown that a lower ϕ value should be used for the shear yielding region, while a higher ϕ value would be acceptable for the elastic shear buckling region. This could be attributed to the small sample sizes available in the shear yielding region. More calibrations should be carried out to examine if this is a persistent trend.

In order to avoid confusion, the use of different ϕ and Ω factors for different failure modes should be avoided. The equations used must therefore minimize any unconservative use of ϕ and Ω. The equations proposed in Appendix C of this study are able to minimize the use of unconservative ϕ and Ω values and provide a more realistic trend between failure zones.

7 REFERENCES

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Appendix A: CSA S136-94 Shear Equations [4]

6.4.5 Shear in Webs

The factored shear resistance, V_r, of a web shall be determined by

$$V_r = \phi A_w F_v$$

where F_v is determined as follows:

(a) when $H \leq \sqrt{k_v E/F_y}$

$$F_v = 0.64\ F_y$$

(b) when $\sqrt{k_v E/F_y} < H \leq 1.41\sqrt{k_v E/F_y}$

$$F_v = \frac{0.641\sqrt{k_v F_y E}}{H}$$

(c) when $H > 1.41\sqrt{k_v E/F_y}$

$$F_v = \frac{\pi^2 E k_v}{12(1-\mu^2)H^2}$$

where

A_w = area of web

F_v = shear limit stress

F_y = yield strength of web material

H = h/t

h = flat dimension of web measured in the plane of the web

k_v = shear buckling coefficient determined as follows:

- (i) for unreinforced webs, $k_v = 5.34$; and
- (ii) for beam webs with transverse stiffeners satisfying the requirements of Clause 6.5

$$k_v = 4 + \frac{5.34}{(a/h)^2} \text{ when } a/h \leq 1.0\text{; and}$$

$$k_v = 5.34 + \frac{4}{(a/h)^2} \text{ when } a/h > 1.0$$

a = distance between transverse stiffeners

t = thickness of web

Where the web consists of two or more sheets, each sheet shall be considered as a separate member carrying its share of the shear.

Appendix B: AISI-96 Shear Equations [5]

C3.2 Strength for Shear Only

The nominal shear strength, V_n, at any section shall be calculated as follows:

(a) For $h/t \leq 0.96\sqrt{Ek_v/F_y}$

$V_n = 0.60F_yht$ (*Eq.* C3.2-1)

$\Omega_v = 1.50$ (ASD)

$\phi_v = 1.0$ (LRFD)

(b) For $0.96\sqrt{Ek_v/F_y} < h/t \leq 1.415\sqrt{Ek_v/F_y}$

$V_n = 0.64t^2\sqrt{k_vF_yE}$ (*Eq.* C3.2-2)

$\Omega_v = 1.67$ (ASD)

$\phi_v = 0.90$ (LRFD)

(c) For $h/t > 1.415\sqrt{Ek_v/F_y}$

$$V_n = \frac{\pi^2 E k_v t^3}{12(1-\mu^2)h} = 0.905Ek_vt^3/h \qquad (\textit{Eq. } \text{C3.2-3})$$

$\Omega_v = 1.67$ (ASD)

$\phi_v = 0.90$ (LRFD)

where

V_n = Nominal shear strength of beam

t = Web thickness

h = Depth of the flat portion of the web measured along the plane of the web

k_v = Shear buckling coefficient determined as follows:

1. For unreinforced webs, $k_v = 5.34$
2. For beam webs with transverse stiffeners satisfying the requirements of Section B6

when $a/h \leq 1.0$

$$k_v = 4.00 + \frac{5.34}{(a/h)^2} \qquad (\textit{Eq. } \text{C.3.2-4})$$

when $a/h > 1.0$

$$k_v = 5.34 + \frac{4.00}{(a/h)^2} \qquad (\textit{Eq. } \text{C3.2-5})$$

where

a = the shear panel length for unreinforced web element

= the clear distance between transverse stiffeners for reinforced web elements.

For a web consisting of two or more sheets, each sheet shall be considered as a separate element carrying its share of the shear force.

Appendix C: Proposed Shear Equations

C3.2.1 Shear Strength of Webs Without Holes

The nominal shear strength, V_n, shall be calculated as follows:

$$V_n = A_w F_v \qquad (Eq.\ C3.2.1\text{-}1)$$

(a) For $h/t \le \sqrt{Ek_v / F_y}$

$$F_v = 0.60 F_y \qquad (Eq.\ C3.2.1\text{-}2)$$

(b) For $\sqrt{Ek_v / F_y} < h/t \le 1.51\sqrt{Ek_v / F_y}$

$$F_v = \frac{0.60\sqrt{Ek_v F_y}}{(h/t)} \qquad (Eq.\ C3.2.1\text{-}3)$$

(c) For $h/t > 1.51\sqrt{Ek_v / F_y}$

$$F_v = \frac{\pi^2 E k_v}{12(1-\mu^2)(h/t)^2} = 0.904Ek_v/(h/t)^2 \qquad (Eq.\ C3.2.1\text{-}4)$$

$\Omega_v = 1.62$ (ASD)

$\phi_v = 0.95$ (LRFD)

where

A_w = Area of web element = (ht)

F_v = Nominal shear stress

V_n = Nominal shear strength

t = Web thickness

h = Depth of flat portion of web measured along plane of web

k_v = Shear buckling coefficient determined as follows:

1. For unreinforced webs, $k_v = 5.34$
2. For webs with transverse stiffeners satisfying the requirements of Section B6

when $a/h \le 1.0$

$$k_v = 4.00 + \frac{5.34}{(a/h)^2} \qquad (Eq.\ C3.2.1\text{-}5)$$

when $a/h > 1.0$

$$k_v = 5.34 + \frac{4.00}{(a/h)^2} \qquad (Eq.\ C3.2.1\text{-}6)$$

where

a = Shear panel length of unreinforced web element

= Clear distance between transverse stiffeners of reinforced web elements.

For a web consisting of two or more sheets, each sheet shall be considered as a separate element carrying its share of the shear force.