ASCE Design Standard for Stainless Steel Structures

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by

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I. INTRODUCTION

Cold-formed stainless steel sections have gained increasing use in architectural and structural applications in recent years due to their superior corrosion resistance, ease of maintenance, and attractive appearance. Typical applications include curtain wall panels, mullions, door and window framing, roofing and siding, stairs, cars and trucks, and a variety of special uses (Ref. 21).

Due to the difference in material properties between stainless and carbon steels, a separate design specification for stainless steel structural members is needed. The first edition of the Specification for the Design of Light Gage Cold-Formed Stainless Steel Structural Members was published by American Iron and Steel Institute (AISI) in 1968 (Ref. 4). The current edition of the AISI design specification (Ref. 5) was issued in 1974 to include design provisions for structural members cold-formed from sheet, strip, plate or flat bar, annealed and cold-rolled grades of Types 201, 202, 301, 302, 304, and 316 austenitic stainless steels.

Recently, the probability-based Load and Resistance Factor Design (LRFD) criteria have been successfully applied to the structural design of hot-rolled steel shapes and built-up members (Refs. 1, 17, 27). The AISI LRFD Specification is being developed for the design of structural members cold-formed from carbon and low alloy steels (Refs. 18, 19, 24, 25). These design criteria are based on the limit states of strength and serviceability of the structure. They can provide a more uniform degree of structural safety and a consistent reliability for different design situations.

In order to update the Allowable Stress Design (ASD) Specification and to develop the new LRFD Specification for cold-formed stainless steel members, a research project has been conducted at the University of Missouri-Rolla since 1986 under the sponsorship of the American Society of Civil Engineers (ASCE). This project contains the following two phases:

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1) To prepare an ASCE ASD specification for the design of structural members cold-formed from austenitic and ferritic stainless steels.
2) To develop the new ASCE LRFD specification for the design of cold-formed stainless steel structural members.

Based on the results of previous tests conducted at Cornell University by Johnson, Wang, Errera, Winter, Tang and Popowich (Refs. 15, 16, 20, 31, 32) and the current AISI specifications for the design of cold-formed stainless steel and carbon steel structural members (Refs. 5, 3), the ASCE ASD specification has been prepared and proposed in Ref. 22. The second phase of the research project is concentrated on the development of LRFD criteria.

II. ALLOWABLE STRESS DESIGN (ASD) SPECIFICATION

The proposed ASCE Allowable Stress Design Specification (Ref. 22) is limited to the use of structural members cold-formed from stainless steel sheet, strip, plate or flat bar, annealed and cold-rolled in 1/16-, 1/4-, and 1/2-hard tempers. This Specification is intended for building applications and can also be used for other structures if appropriate allowances are made for dynamic effects.

The design provisions of the ASD Specification are given in terms of allowable moments and loads instead of allowable stresses. The allowable strength is determined by applying a factor of safety to the computed nominal strength. For the design of cold-formed stainless steel structural members, the basic safety factors used for flexural members, compression members, bolted connections, and welded connections are 1.85, 2.15, 2.4, and 2.5, respectively. These factors are relatively larger than those used for cold-formed carbon steel members.

Due to the significant differences in material properties between stainless and carbon steels, the AISI Specification for the Design of Cold-Formed Steel Structural Members (Ref. 3) and the AISC Specification for the Design, Fabrication and Erection of Structural Steel for Buildings (Ref. 2) do not apply to the design of stainless steel structural members.

The following discussion deals with some major design considerations proposed in the ASCE ASD Specification. Other design information can be found in Ref. 22.

1. Materials

Some of the significant differences in material properties between cold-formed stainless and carbon steels are: (1) pronounced anisotropic characteristics, (2) difference in stress-strain relationships for different grades of stainless steels, (3) low proportional limits, and (4) pronounced response to cold work. It should be noted that stainless steels have different stress-strain curves in the longitudinal and transverse directions for tension and compression modes of stress. These curves are always of gradually yielding type accompanied by relatively low proportional limits. As a result, the buckling stresses in the inelastic region become more important for the design of cold-formed stainless steel structural members.

The proposed ASCE ASD Specification includes four types of austenitic stainless steels (Types 201, 301, 304, and 316) and three types of ferritic stainless steels (Types 409, 430, and 439). Other stainless steels may also be used for cold-formed structural members, provided that they satisfy the requirements stipulated in the Specification.

The American Society for Testing and Materials (ASTM) is the basic source of stainless steel designations for the ASCE Specification, in which references are made to ASTM Specifications A666 (Ref. 6), A176 (Ref. 7), A240 (Ref. 8), and A276 (Ref. 9). Table 1 lists the design yield strengths, F_y, for seven types of stainless steels included in the Specification. It should be noted that for Types 409, 430, and 439 ferritic stainless steels, the listed yield strengths are based on the minimum values specified in the ASTM Specification (Ref. 8). These values are excessively lower than the tested data given in Table 2 on the basis of Refs. 28, 29, and 30.

For the design of cold-formed stainless steel structural members, the required secant modulus (E_s), tangent modulus (E_t), and plasticity reduction factors corresponding to different stress values are given in the design tables and figures of the allowable stress design specification (Ref. 22). Tables 3 and 4 list the initial modulus of elasticity (E_o) and initial shear modulus (G_o) for seven types of stainless steels, respectively.

2. Effective Design Width Formulas

In the proposed ASCE ASD Specification, the effective design width approach is applied to both stiffened and unstiffened compression elements. It is the same approach used in the current design criteria for cold-formed carbon steel structural members (Ref. 3) except that consideration has been given to the type of stress (longitudinal compression or transverse compression).

In view of the fact that a pleasing appearance is one of the important considerations in stainless steel design, the maximum permissible flat-width-to-thickness ratios (w/t) stipulated in this Specification have been reduced in order to minimize the possible local distortion of the flat element.

(a) Stiffened Compression Elements

The effective design width of the uniformly compressed stiffened element is determined on the basis of Winter's effective design width formula (Ref. 33) as given in Eq. (1). This formula has been verified by Johnson and Wang for use in stainless steel members (Refs. 20, 31).

$$b/t = 1.9 \sqrt{E_o/f} \left[1-0.415 \sqrt{E_o/f} /(w/t)\right] \quad (1)$$

In Eq. (1), b is the effective design width, E_o is the initial modulus of elasticity as given in Table 3, f is the compressive stress at the edge, w is the flat width of the element, and t is the element thickness. Because Eq. (1) compared favorably with the experimental data obtained from numerous stainless steel beam and column tests as reported in Ref. 31 for temper grades, this equation was used in the 1974 Edition of the AISI Specification for the design of stainless steel structural members.

In the proposed ASCE Specification, Eq. (1) is expressed in terms of the b/w ratio and the slenderness factor λ as follows:

$$b/w = (1/\lambda)(1 - 0.22/\lambda) \tag{2}$$

where λ is a slenderness factor determined by Eq. (3):

$$\lambda = \sqrt{f/\sigma_{cr}} \tag{3}$$

In Eq. (3), σ_{cr} is the critical local buckling stress given by the following expression:

$$\sigma_{cr} = \frac{\pi^2 k \eta E_o}{12(1-\mu^2)(w/t)^2} \tag{4}$$

where k is the buckling coefficient, η is the plasticity reduction factor used for the inelastic buckling, and μ is the Poisson's ratio. The plasticity reduction factor varies with the types of loading and the edge support conditions. Although the plasticity reduction factor is needed in the inelastic range (Ref. 13), it has been shown that the factor η can be taken as a unity for cold-formed stainless steel members having stiffened and unstiffened compression elements (Ref. 31). Consequently, the slenderness factor λ can be computed by using Eq. (5) for η = 1.0.

$$\lambda = (1.052/\sqrt{k})\ (w/t)\ (\sqrt{f/E_o}) \tag{5}$$

In the above equation, the buckling coefficient, k, is taken as 4.0 for long, stiffened elements supported by a web on each longitudinal edge.

(b) Unstiffened Compression Elements

The effective design width approach is also proposed for the design of members consisting of unstiffened compression element in the ASCE ASD Specification. Equations (2) and (5) are equally employed for the uniformly compressed unstiffened element, except that the buckling coefficient is taken as 0.5. This k value is slightly higher than the theoretical value of 0.43, which is being used in the AISI specification for the design of cold-formed carbon steel structural members.

3. Beam Design

(a) Bending Strength

The design provisions of the proposed ASCE ASD Specification for beam design are written in terms of the allowable moment instead of the allowable bending stress. Section 3.3 of the Specification gives the following equations for determining the nominal strengths. The factor of safety used for computing the allowable moment for cold-formed stainless steel flexural members is 1.85.

(i) Nominal Section Strength

For section strength based on initiation of yielding, the nominal moment, M_n, can be calculated as follows:

$$M_n = S_e F_y \tag{6}$$

in which, S_e is the elastic section modulus of the effective section and F_y is the design yield strength. The elastic section modulus is calculated on the basis of the effective width formulas given in Eqs. (2) and (5) with the extreme compression or tension fiber at the yield stress of F_y.

(ii) Lateral Buckling Strength

For doubly- or singly-symmetric sections subject to lateral buckling, the nominal moment, M_n, can be determined as follows:

$$M_n = M_c(S_c/S_f) \tag{7}$$

where S_f is the elastic section modulus of the full, unreduced section for the extreme compression fiber, S_c is the elastic section modulus of the effective section calculated at a stress M_c/S_f in the extreme compression fiber, and M_c is the critical moment due to lateral buckling.

Additional design expressions for determining the critical moment M_c are included in the Specification. For singly-symmetric sections bending about the axis of symmetry or bending about the axis perpendicular to the symmetry axis, theoretical formulas are used to determine the critical moments. In addition, the effect of local buckling on lateral buckling strength is considered in this design provision by using the ratio of the effective section modulus to the full section modulus, S_c/S_f. This approach is adopted from the current AISI Specification for cold-formed carbon and low alloy steels (Ref. 3).

The critical moments, M_c, discussed above are limited to M_y, which is the maximum moment causing initial yielding at the extreme compression fiber of the full section. In order to account for the inelastic response of stainless steels, a plasticity reduction factor, E_t/E_o, was introduced in various formulas for lateral buckling in the inelastic range.

(b) Shear Strength

According to the design provision of the proposed allowable stress design specification, the design shear strength at any section shall not exceed the allowable shear force, V_a, calculated as follows:

$$V_a = \frac{2.61E_o t^3 (G_s/G_o)}{h} \leq 0.61F_{yv}ht \qquad (8)$$

where G_s is the shear secant modulus, G_o is the initial shear modulus as given in Table 4, F_{yv} is the shear yield strength as given in Table 1, and h is the depth of the flat portion of the web measured along the plane of the web.

The allowable shear force given in Eq. (8) is determined from the product of the allowable shear buckling stress (F_v) and the cross-sectional area of web (hxt). The critical buckling stress for shear of a flat element can be expressed by Eq. (4), in which σ_{cr} is replaced by τ_{cr}, and w is changed to h. The shear buckling coefficient, k, is taken as 5.35 for a long plate having simply supported conditions. The plasticity reduction factor, G_s/G_o, is used to reflect the shear buckling behavior of stainless steel in the inelastic range (Ref. 5). Substituting the values discussed above, assuming $\mu = 0.3$ and applying a safety factor of 1.85, the allowable shear buckling stress, F_v, is obtained. The maximum allowable shear stress, $0.61F_{yv}$, given in Eq. (8) is determined by dividing the shear yield strength by a safety factor of 1.64. This smaller safety factor has been chosen to reflect the less serious nature of shear yielding in comparison with yielding in tension and compression.

(c) Web Crippling Strength

The design provisions for web crippling and combined bending with web crippling are based on the current AISI Specification (Ref. 3) for the design of cold-formed carbon steel members. However, the factors of safety used to determine the allowable web crippling strength of stainless steel members are 2.0 and 2.2 for shapes having single webs and I-sections, respectively. These factors are slightly larger than those used for cold-formed carbon steel members.

4. Column Design

The design provisions of the proposed ASCE ASD Specification for column design are written in terms of the allowable load instead of the allowable compressive stress. The Specification contains the following equation to determine the nominal axial load P_n.

$$P_n = A_e F_n \qquad (9)$$

where A_e is the effective area calculated at the stress F_n, and F_n is the least of the flexural, torsional, and torsional-flexural buckling stresses as discussed below. For computing the allowable load for the design of stainless steel columns, the safety factor is 2.15.

(a) Flexural Buckling

For sections subject to flexural buckling only, the buckling stress, F_n, can be determined as follows:

$$F_n = \frac{\pi^2 E_t}{(KL/r)^2} \leq F_y \qquad (10)$$

In Eq. (10), E_t is the tangent modulus corresponding to the buckling stress F_n, K is the effective length factor, L is the unbraced length of the member, and r is the radius of gyration of the full, unreduced cross section.

The tangent modulus is used for flexural column buckling in the inelastic range. An iterative process is needed in Eq. (10) to determine the correct buckling stress. Design tables and figures for E_t are provided in the proposed specification. For the purpose of simplicity, the tangent modulus may be determined by using the modified Ramberg-Osgood equation (Ref. 23). When a member is subjected to elastic buckling, E_t is simply replaced by E_o in Eq. (10). For short, compact columns, the yield strength, F_y, governs the design. Otherwise, the effect of local buckling on column strength is taken into account by using the effective area, A_e, as given in Eq. (9).

(b) Torsional and Torsional-Flexural Buckling

For doubly- or point-symmetric sections subject to torsional buckling, and for singly-symmetric sections subject to torsional-flexural buckling, new design formulas are included in the proposed Specification for determining the critical buckling stresses, F_n. These formulas are adopted from the current AISI Specification for carbon and low alloy steels with some necessary modifications. The plasticity reduction factor, E_t/E_o, was applied to the design equations to determine the buckling stress of stainless steels in the inelastic range.

5. Beam-Columns

The design provision in the proposed ASCE ASD Specification was adopted from Ref. 3 for the design of cold-formed carbon steel members, except that the tangent modulus, E_t, is used to calculate the critical buckling load. Appropriate safety factors should be used for determining the allowable load and allowable moment.

6. Cylindrical Tubular Members

Section 3.6 of the proposed ASCE ASD Specification can be used for the design of cylindrical tubular members having a ratio of outside diameter to wall thickness (D/t) not greater than $0.881E_o/F_y$. For members subject to bending, the nominal moment is based on the ratio of $(E_o/F_y)(t/D)$. The buckling stress of cylindrical tubular members in the inelastic range is dependent on the ratio of the effective proportional limit-to-yield strength, F_{pr}/F_y, for different grades of stainless steels.

The design expression for determining the axial load of stainless steel cylidrical tubular members is given by the product of the effective area and the flexural buckling stress. The formula used to determine the effective area is similar to that used in Ref. 3 except that the plasticity reduction factor, E_t/E_o, is applied for cold-formed stainless steels. For combined bending and compression, the design requirements shall satisfy the design provision for beam-columns.

Same as other types of stainless steel structural members, the safety factors used for determining the allowable axial load in compression and allowable moment are 2.15 and 1.85, respectively.

7. Connections

The proposed ASCE Specification includes design provisions for welded and bolted connections using stainless steels. These design provisions were based on the results of the experimental data obtained from the test program conducted at Cornell University by Errera, Tang, Popowich, and Winter (Refs. 15, 16).

(a) Welded Connections

The design requirements for using butt welds, fillet welds, and resistance welds are provided in the proposed ASCE Specification. The factor of safety against fracture of connected parts is taken as 2.5 for the sake of consistency with the design of cold-formed stainless steel members. The design of fillet welds is based on the shear strengths of the annealed base metal and the weld metal. Because transverse fillet welds are stressed more uniformly than longitudinal fillet welds, the capacities of fillet welds subject to transverse loading were found to be higher than that for longitudinal loading. This finding has been reflected in the Specification for the design of transverse fillet welds. The allowable shear strength of resistance welds was adopted from the AWS Recommended Practices of Resistance Welding (Ref. 11)

(b) Bolted Connections

The design requirements for bolted connections deal with a) the minimum spacing and edge distance, b) tension in connected parts, c) bearing in bolted connections, and d) shear and tension in bolts. The factor of safety used for bolted connections is taken as 2.4. These design provisions were derived on the basis of four types of failure modes observed from the results of tests (Ref. 16). The minimum edge distance of each individual connected part, e_{min}, is to prevent the shear failure of connected parts.

To prevent tension failure in the connected parts, two separate design equations are given for double and single shear connections. The allowable bearing stresses are determined on the basis of the longitudinal tensile strength, F_u, of connected parts. Different bearing stresses are specified for single and double shear connections. The allowable shear and tension stresses in stainless steel bolts are specified according to the ASTM Specifications A276 and A193 requirements (Refs. 9, 10).

III. DEVELOPMENT OF LRFD CRITERIA FOR STAINLESS STEELS

The LRFD method is an improved approach for the design of steel structures because it involves probabilistic treatments for uncertain variables in the design formulas. The theoretical basis of this design method has been established and can be found in numerous references (Refs. 12, 14, 26, 27). Basically, the model of the failure probability is used to determine the risk of failure of structures. The safety index, β, derived from the probability of failure is used as a relative measure of the safety for design. The LRFD criteria can be based on the first order probabilistic design approach, for which only mean value and coefficient of variation of variables are required. These variables reflect the uncertainties in mechanical properties, loading, design, and fabrication. The LRFD criteria for the design of stainless steel structural members and connections are being developed by the authors. It is expected that the proposed LRFD specification will be completed in 1989.

IV. CONCLUSIONS

The ASCE allowable stress design specification for cold-formed stainless steel structural members with its commentary has been prepared and reported in Ref. 22. This paper briefly summarizes some of the design provisions which are proposed in the ASCE ASD Specification for the use of four types of austenitic stainless steels and three types of ferritic stainless steels. Some of the major differences of design provisions between stainless and carbon steel specifications are also cited. The LRFD criteria are being developed for the design of cold-formed stainless steel structural members and connections.

V. ACKNOWLEDGMENTS

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A_e	= Effective area
b	= Effective width
e_{min}	= Minimum edge distance from edge
E_o	= Initial modulus of elasticity
E_s	= Secant modulus
E_t	= Tangent modulus
f	= Compressive stress at the edge of the element
F_n	= Nominal buckling stress
F_{pr}	= Effective proportional limit
F_u	= Tensile strength
F_v	= Allowable shear buckling stress
F_y	= Yield strength
F_{yv}	= Shear yield strength
G_o	= Initial shear modulus
G_s	= Shear secant modulus
h	= Depth of the flat portion of the web measured along the plane of the web
k	= Buckling coefficient
K	= Effective length factor
L	= Unbraced length of the member
M_c	= Critical moment
M_n	= Nominal moment
P_n	= Nominal axial load
r	= Radius of gyration
S_c	= Elastic section modulus of the effective section calculated at a stress M_c/S_f in the extreme compression fiber
S_e	= Elactic section modulus of the effective section
S_f	= Elastic section modulus of full, unreduced section
t	= Thickness of the element
V_a	= Allowable shear force
w	= Flat width of the element
σ_{cr}	= Critical buckling stress
τ_{cr}	= Critical buckling stress for shear
β	= Safety index
η	= Plasticity reduction factor
μ	= Poisson's ratio
λ	= Slenderness factor

TABLE 1

Design Yield Strengths

Type of Stress	F_y, ksi					
	Types 201, 301, 304, and 316 +					Types 409, 430 and 439 ++
	Annealed	1/16-Hard		1/4-Hard	1/2-Hard	
Longitudinal Tension	30	40*	45	75	110	30
Transverse Tension	30	40*	45	75	110	30
Transverse Compression	30	40*	45	90	120	30
Longitudinal Compression	30	36*	41	50	65	30
Shear Yield Strength, F_{yv}	17	23*	25	42	56	17

1 ksi = 6.895 MPa

\+ Based on ASTM A666-84.
++ Based on ASTM A240-86.
* Flat bars.

TABLE 2

Tested Mechanical Properties of Ferritic Stainless Steels

Type of Stainless Steels	Yield Strength F_y		Tensile Strength F_u		No. of Tests	Ref. No.
	Mean (ksi)	St. Dev. (ksi)	Mean (ksi)	St. Dev. (ksi)		
Type 409						
LT	34.2	2.50	58.6	1.93	15	30
TT	39.7	3.33	64.3	2.70	4977	28,30
LC	34.9	2.06			14	30
TC	36.8	3.05			12	30
Types 430 and 439						
LT	45.8	1.74	74.7	0.82	26	30
TT	52.2	3.92	78.4	4.23	4209	28,29,30
LC	45.6	2.92			29	30
TC	52.3	1.99			27	30

1 ksi = 6.895 MPa;
St. Dev. = Standard Deviation.
LT. = Longitudinal Tension; TT. = Transverse Tension.
LC. = Longitudinal Compression; TC. = Transverse Compression.

Note: For Types 409, 430, and 439 ferritic stainless steels, Ref. 8 specifies a minimum yield strength of 30 ksi in transverse tension for plate, sheet, and strip.

TABLE 3

Initial Moduli of Elasticity

Type of Stress	Initial Modulus of Elasticity, E_o, ksi x 10^3		
	Types 201, 301, 304, and 316		Types 409, 430, and 439
	Annealed & 1/16-Hard	1/4-Hard & 1/2-Hard	
Longitudinal Tension	28.0	27.0	27.0
Transverse Tension	28.0	28.0	29.0
Transverse Compression	28.0	28.0	29.0
Longitudinal Compression	28.0	27.0	27.0

1 ksi = 6.895 MPa

TABLE 4

Initial Shear Moduli

Type of Stress	Initial Shear Modulus, G_o, ksi x 10^3		
	Types 201, 301, 304, and 316		Types 409, 430, and 439
	Annealed & 1/16-Hard	1/4-Hard & 1/2-Hard	
Longitudinal Tension	10.8	10.5	10.5
Transverse Tension	10.8	10.8	11.2
Transverse Compression	10.8	10.8	11.2
Longitudinal Compression	10.8	10.5	10.5

1 ksi = 6.895 MPa