

Development of design rules in the AISC Design Guide for Structural Stainless Steel

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Abstract

This paper describes the development of an AISC (American Institute of Steel Construction) Design Guide for hot rolled and welded structural stainless steel sections. Where stainless steel behaves in a similar way to carbon steel, the Design Guide simply refers to the relevant section in ANSI/AISC 360-10 *Specification for Structural Steel Buildings*. Where the guidance in the AISC Specification would be unconservative when applied to stainless steel, specific rules for stainless steel were derived and presented in a format as close as possible to the equivalent expressions in AISC 360. The stainless steel design rules were calibrated against an extensive database of test results on members and connections. A full reliability analysis was carried out to calculate the LRFD resistance factors; in most cases, the carbon steel resistance factors were shown to be applicable to stainless steel also.

Keywords

Stainless steel, design specification, AISC, reliability, resistance factors, structural members

1 Background

Stainless steels are increasingly used in construction because they are highly corrosion resistant and attractive, while having good strength, toughness and fatigue properties in combination with low maintenance requirements. They are used in aggressive environments, for example applications near salt water, exposed to deicing salts or in very heavily polluted locations. Industrial structures like platforms, barriers, gates and equipment supports for the food and beverage, water treatment, pulp and paper, nuclear, biomass, chemical and pharmaceutical industries are often made from stainless steels. They are also used for pedestrian and vehicular bridge components exposed to aggressive environments. Stainless steel structural components are a popular choice for supporting glass curtain walls, as well as for roofs, canopies, seismic components, security barriers and other applications that need good corrosion resistance and strength to reduce maintenance requirements and improve safety. They are widely used for hand railing and street furniture for the same reasons.

Figures 1 to 8 show examples of recent structural applications of stainless steel.

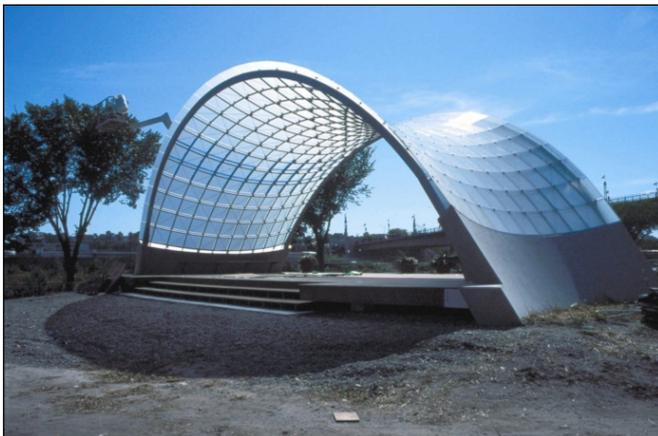


Fig. 1 Schubert Club Band Shell, St. Paul, Minnesota

Photo: Skidmore, Owings & Merrill LLP



Fig. 2 Stainless steel frame in nuclear power plant

Photo: Stainless Structurals LLC

The yielding and work-hardening characteristics of stainless steels mean that conventional carbon steel design rules based on observing the limit of elastic deformation do not apply; the elastic 'limit' of stainless steels is not sharply defined as they work-harden rather than yield with the onset of plastic deformation. Since early structural applications in the 1920's like the reinforcement chain around the dome of St Paul's Cathedral in London, structural engineers have been addressing the challenge of developing appropriate rules in design codes which enable the maximum advantage to be taken of stainless steel properties.



Fig. 3 Stainless steel staircase in brewery
Photo: Stainless Structurals LLC



Fig. 4 Stainless steel sign support, Tampa
Photo: TriPyramid Structures, Inc.

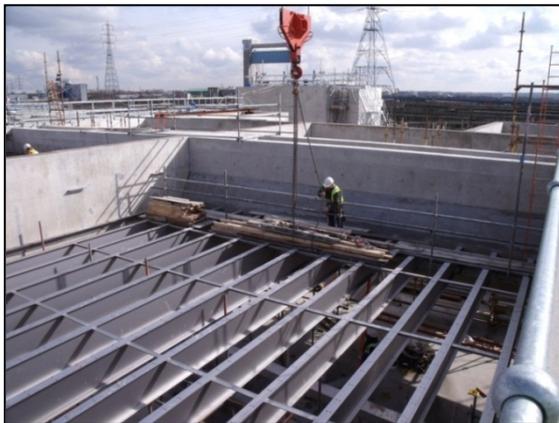


Fig. 5 Stainless steel I-shaped beams at Thames Gateway Water Treatment Works
Photo: Interserve

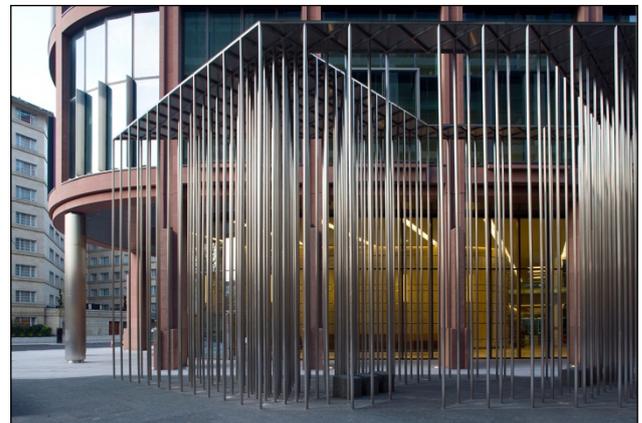


Fig. 6 Stainless steel columns in The Pavilion, Regents Place, London
Photo: Arup



Fig. 7 Harbor Drive Pedestrian Bridge, San Diego, US
Photo: Brooke Duthie photography & T.Y. Lin International



Fig. 8 Stainless steel railway bridge, Añorga, Spain
Photo: Outokumpu

2 Introduction to AISC Design Guide: Structural Stainless Steel

Although an SEI/ASCE Specification for the Design of Cold-Formed Stainless Steel Structural Members has been available for many years [1], there is no US design specification covering hot rolled and welded stainless steel. This has been a major obstacle to the wider use of stainless steel structures, forcing designers and owners to conduct their own investigations or abandon stainless steel in favour of alternative materials which have readily available design guidance and specification rules. Designers determined to use stainless steel have either been required to work from first principles, or use carbon steel rules, sometimes applying an arbitrary additional safety factor. This is unsatisfactory;

working from first principles is wasteful of the designer's time and application of carbon steel rules with an extra safety factor is unlikely to lead to economic design with a consistent level of reliability.

In 2009, work started on the development of an AISC Design Guide for structural stainless steel, supported by the US stainless steel industry and associated market development associations [2]. The motivation behind the project was that the availability of design guidance for structural stainless steel aligned to US codes would facilitate greater and more efficient use of hot rolled and welded products in the Americas and other parts of the world, which use US AISC design specifications with little or no modification.

The AISC Design Guide was written so that designers who are familiar with ANSI/AISC 360-10 *Specification for Structural Steel Buildings* [3] would be able to use it without any difficulty. Where stainless steel behaves in a similar way to carbon steel, the Design Guide simply refers to the relevant section in AISC 360. Where the guidance in the AISC Specification would be unconservative or unduly conservative when applied to stainless steel, specific rules for stainless steel have been presented in a format as close as possible to the equivalent expressions in the AISC 360 for carbon steel.

The AISC Design Guide is intended for the design of primary and secondary structural components. It covers aspects of material properties, grade selection and durability. Design rules for members and connections (bolted and welded) are given at ambient temperatures and in fire. Guidance on fatigue, fabrication and erection are given also. For special structures such as those in nuclear installations or pressure vessels, additional requirements may need to be considered, which are outside the scope of the Design Guide.

The guidance relates to common hot rolled and welded sections (I-sections, Channels, T-sections, round, square and rectangular Hollow Structural Sections (HSS) and angles) with thickness 0.125 in. (3 mm) and greater. In accordance with AISC 360, the Design Guide gives guidance in two formats: LRFD (Load and Resistance Factor Design) philosophy and ASD (Allowable Stress Design). The Design Guide specifically covers the popular austenitic grades 304/304L and 316/316L and the standard and lean duplex grades. Guidance is also included on the use of certain precipitation hardening grades for tension members, fixings and fasteners (these stainless steels are useful when very high strengths are needed). The Design Guide refers to AISC, ASTM and other US and internationally relevant standards and reference documents for information outside the scope of the Design Guide. Not surprisingly, the scope of the design rules is more limited than the scope of AISC 360; they cover commonly encountered structural shapes and load scenarios, but not every scenario in AISC 360. At the end of the Design Guide, six design examples are given which illustrate the application of the design rules.

Stainless steel's non-linear stress-strain relationship means that certain carbon steel design rules require modification, for example some local buckling limits, member buckling curves and methods for estimating deflection of beams. As well as nonlinearity, the stress-strain characteristics of stainless steels also display non-symmetry of tensile and compressive behaviour and anisotropy (differences in behaviour of coupons aligned parallel and transverse to the rolling direction). In general, anisotropy and non-symmetry increase with cold work and so are more significant in the design of lighter gauge heavily worked sections, which are covered by SEI/ASCE 8. The structural sections covered by the AISC Design Guide are not made from heavily cold worked material and so the differences in the stress-strain behaviour due to non-symmetry and anisotropy are not large; the nonlinearity has a more significant effect.

The following procedure was followed for deriving the design rules for stainless steel in the AISC Design Guide:

1. Compare the rules for carbon steel in AISC 360 against all available stainless steel test data on members and connections.
2. Modify the AISC 360 carbon steel rules to suit the stainless steel data, where necessary
3. Calculate the stainless steel resistance factors to use with the recommended stainless steel design rules.

Eurocode 3: Part 1.4 (EN 1993-1-4) [4] is the only other design standard available in the English language covering hot rolled and welded structural stainless steels; the Eurocode 3 design rules were therefore also taken into account throughout the process of deriving the rules for the AISC Design Guide. The basis and justification of the Eurocode design rules are explained in the Commentary to the European Design Manual for Structural Stainless Steel [5] along with a full set of references. The Eurocode design rules are based on work primarily carried out in the 1980s and 1990s, and over the last two years the EN 1993-1-4 Evolution Group has prepared a number of amendments to this standard, most of which will lead to less conservative design rules due to the far greater body of test data which is now available for structural stainless steel. The amendments cover section classification, the extension of the rules to cover lean duplexes, and less conservative rules for the resistance of stocky cross-sections and also for shear buckling. Many of these proposed developments were taken into account during the preparation of the AISC Design Guide.

3 Determination of Stainless Steel Resistance Factors in the AISC Design Guide

3.1 Probabilistic basis and reliability index

The AISC method for assessing the reliability of a structure is described in Lin *et al* [6]. Structural safety is a function of the resistance R of the structure as well as the load effects Q . The resistance and the load effects are considered to be random variables. Based on the assumed probability distributions and first-order probabilistic theory, the reliability index β can be expressed as:

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

where

Q_m = mean value of the load effect

R_m = mean value of the resistance

V_Q = coefficient of variation of the loading (i.e., standard deviation \div mean)

V_R = coefficient of variation of the resistance (i.e., standard deviation \div mean)

In accordance with the assumptions made in the development of the LRFD approach for hot rolled steel structures in AISC 360, a target reliability index was set for members of $\beta = 2.6$ and for connections $\beta = 3.5$ [7].

3.2 Loading

A dead load factor of 1.2 and a live load factor of 1.6 for the basic combination of ‘dead plus live’ load were assumed in the stainless steel reliability analysis. The analyses were carried out for a ‘dead to live’ load ratio of 1:5 and 1:3. For all modes of loading, the load ratio 1:5 gave very slightly more severe results. However, in accordance with the assumptions taken for the reliability analysis carried out for AISC 360, the values for a ‘dead to live’ load ratio of 1:3 are considered more applicable for hot rolled and welded structural sections [7] and were thus used to calculate the resistance factors.

Q_m and V_Q were calculated from the following equations given in Ellingwood *et al* [8]. These expressions were also used by Lin *et al* [6].

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

where

c = influence coefficient which transfers load intensities to load effects

The following values for the parameters were adopted:

$$D_m = 1.05D_n, \quad V_D = 0.1, \quad L_m/L = 1.0 \quad V_L = 0.25.$$

The subscripts m , n , D and L refer to ‘mean’, ‘nominal’, ‘dead’ and ‘live’ respectively. Assuming a ‘dead to live’ ratio of 1:3 gives $V_Q = 0.19$ and $Q_m = 1.35cL_n$,

3.3 Resistance

The randomness of the resistance R of a structural element is due to the variability inherent in the mechanical properties of the material, variations in dimensions, and the uncertainties in the design theory used to express the member strength. The mean resistance of a structural member, R_m is defined as follows:

$$R_m = R_n(M_m)(F_m)(P_m)$$

where

R_n = nominal resistance of the structural elements

M_m , F_m and P_m are the mean values of the random variables reflecting the uncertainties in material properties (i.e. F_y , F_u , etc), the geometry of the cross-section (i.e. A , t , L etc) and the design assumptions, respectively.

The coefficient of variation of the resistance, V_R , is calculated as the square-root-sum-of-squares of the material, fabrication and design model uncertainty coefficients of variation:

$$V_R = \sqrt{V_m^2 + V_f^2 + V_p^2}$$

3.3.1 Uncertainties in Material Properties (M_m and V_m)

Data on the statistical variation of material strengths were collected from literature, for example [9],[10],[11],[12],[13]. Steel producers and manufacturers of stainless steel sections also supplied data for this analysis. Much of their data was supplied on a confidential basis, so it is not possible to give a detailed breakdown of the material data herein.

The data analysed demonstrate values of the 0.2 % offset yield overstrength ratio $M_m > 1.3$ for austenitic and $M_m > 1.1$ for duplex, where M_m is the ratio of measured strength to nominal (minimum specified) strength. Duplex stainless steels were introduced into standards more recently, so the minimum specified values are based on current steelmaking technology and the gap between the actual and minimum specified values is less than that for austenitics. It is important to note that load-bearing duplex stainless steel represents only approximately 1-3% of the total tonnage of structural stainless steel, with austenitic stainless steels accounting for most of the balance. In order to best utilise the greater conservatism in the assessment of 0.2 % offset yield strength for austenitic stainless steel, it was decided to analyse austenitic and duplex stainless steel as separate populations. For austenitic stainless steel, the M_m is taken as 1.3, while for duplex stainless steel M_m is taken as 1.1.

The choice of $M_m = 1.1$ for the 0.2 % offset yield strength in the cold formed stainless steel specification SEI/ASCE 8 is perhaps surprisingly low. However, the analysis of material data carried out in order to select a value of M_m for this specification, showed that the cold-worked grades 301 and 201 (¼ hard and ½ hard) and ferritic stainless steel grades 409, 430 and 439 all demonstrated considerably lower values of M_m than hot-rolled 304 stainless steel [6]. The cold worked and ferritic grades of stainless steel are not included in this AISC Design Guide.

The coefficient of variation V_m was also calculated from the body of material data collected for this project. A value of 0.105 was taken as representative for both austenitic and duplex stainless steel populations. Parametric studies showed that the value of the resistance factor ϕ strongly correlates with the overstrength ratio M_m whereas variations in V_m only lead to small changes in ϕ . The impact of the coefficient of variation is therefore less significant than the overstrength ratio.

3.3.2 Uncertainties in Geometrical Properties (F_m and V_f)

These factors allow for uncertainties caused by initial imperfections, tolerances and variations in geometric properties and account for the differences between the nominal and manufactured cross-sectional dimensions. F_m is taken as 1.0 in US steel standards and Table 1 shows the values of V_f assumed [1],[3],[14]. Note that the NAS Specification for cold-formed carbon steel assumes a lower value of V_f for welded connections than the other standards.

Table 1 Values of V_f assumed by US steel design standards

	AISC 360-10 [3]	NAS-01 Specification [14]	SEI/ASCE 8-02 [1]
Members	0.05	0.05	0.05
Bolted connections	0.05	0.05	0.05
Welded connections	0.15	0.05	0.15

Data presented by Byfield [15] for carbon steel suggests that it is possible to adopt reduced values of $V_f = 0.022$ for compression members and $V_f = 0.02$ for members in bending. The applicability of these figures for use with stainless steel was investigated by comparing the nominal dimensions to the measured dimensions for the range of sections for which data were gathered as part of the investigation into member performance (referenced in section 5 and 6 of this paper). Different values of V_f were derived for bending and compression modes of failure, depending on the relevant elements of the cross-section for the mode of loading. Taking I-shaped members as an example, the variation in the thickness of the flanges is much more critical to the bending strength than the variation in thickness of the web, whereas for shear failure, the opposite is true. If the variation of thickness of the web is relatively greater than the variation of the flange thickness, then the bending resistance of the section can be expected to vary less than the shear resistance. Table 2 shows the values for V_f calculated for the stainless steel test specimens.

Table 2 Calculated values for the variation of geometric properties V_f for stainless steel members

	Compression ($V_{f,comp}$)	Bending ($V_{f,bending}$)
Rectangular HSS	0.0412	0.0486
Round HSS	0.0325	0.0606
I section	0.0214	0.0495

The data showed that in all cases the values for V_f recommended by Byfield are unconservative for stainless steel. In fact, for the case of round HSS in bending, even the higher value of $V_f = 0.05$ appear to be unconservative. However it was felt that the calculated value was based on rather a small number of round HSS available for study, and might well not be truly representative of a larger population. Therefore, in the absence of a more comprehensive measurement campaign specifically for stainless steel, the values adopted in AISC 360 and SEI/ASCE 8 were adopted.

3.3.3 Uncertainties in the design model (P_m and V_p)

Lin *et al* [6] define a ‘Professional factor’, P_m , which is a measure of the ability of the design model to predict the behaviour of a structural element. The professional factor depends on the failure mode in question, and is defined for each specific mode of loading. Note that currently there are no test data for hot rolled austenitic stainless steel structural sections (a few tests have been carried out on hot rolled ferritic stainless steel sections). The test data used to assess the professional factor were data on (austenitic and duplex) HSS, welded I-shaped members and cold-formed stainless steel sections. As a general rule, it is expected that hot rolled sections will perform better than conventionally welded sections because of the absence of residual stresses developed during welding.

Section 5 and Section 6 report the values for the random variable P_m and V_p determined for members in compression and bending respectively. Similar studies were undertaken for other failure modes, including torsional-flexural buckling, shear buckling, web crushing and crippling and combined moment and compression. The performance of stainless steel connections was also investigated. As mentioned in Section 3.3.1, test data for austenitic and duplex stainless steels were assessed as separate populations. Full details of the reliability analysis are given in Appendix B to the AISC Design Guide.

The values of V_p calculated from the test data were relatively high compared to values for V_m and V_f and thus made the greatest contribution to the overall value of V_R .

3.4 Determination of Resistance Factor

Following the assumptions and procedures described in Lin, Yu and Galambos [16] and Bartlett *et al* [7], the resistance factor was calculated from:

$$\phi = \frac{1.481 M_m F_m P_m}{\exp\left(\beta \sqrt{V_R^2 + V_Q^2}\right)}$$

Using all of the assumptions discussed in the previous section, values of the resistance factor ϕ were derived for each expression in the AISC Design Guide. In general, the reliability analysis showed that the AISC carbon steel resistance factors could be safely used with the AISC stainless steel design curves with the following two exceptions:

- Round HSS in compression (ϕ stainless steel = 0.85, ϕ carbon steel = 0.9)
- Fillet welds (ϕ stainless steel = 0.6, ϕ carbon steel = 0.75)

The safety factor, Ω , for use in Allowable Strength Designs, was calculated in accordance with Reference 17.

4 Section Classification

Both Eurocode 3 and AISC 360 adopt the concept of classification of cross-sections according to their ability to resist local buckling and to sustain load with deformation; Eurocode 3 specifies four classes but in AISC 360 the number of classes is three, with the ‘Compact’ class effectively covering Class 1 and 2 in the Eurocodes.

The limiting width-to-thickness ratios for stainless steel given in the AISC Design Guide were derived by calibration against experimental data (as described in Section 5 and Section 6). They differ from those given for carbon steel in AISC 360 primarily due to the nonlinear stress-strain characteristics of stainless steel. The limits are less conservative than those in EN 1993-1-4 since these latter limits are based on research work completed by the mid 1990’s. Over the last twenty years, considerable further research has been conducted on structural stainless steel. Many additional experimental results on cross-section resistance now exist, including both stub column and bending tests. Analysis of the test data by Gardner and Theofanous [18] reveals that the current slenderness limits in EN 1993-1-4 for stainless

steels are overly conservative and that in many cases harmonisation with the equivalent carbon steel limits are justified. These new limits will be incorporated into the next revision of EN 1993-1-4.

Table 3 compares the section classification limits in AISC 360 for carbon steel with those in the AISC Design Guide. The section classification limits for stainless steel are either the same or more conservative than those for carbon steel. The stainless steel section classification limits are the limits recommended in Reference 18. However, in the cases where the stainless limits were higher than the AISC carbon steel limits (web and flange of HSS in bending, and round HSS in bending), the limits were reduced to match the AISC carbon steel limits.

Table 3 Section classification limits in AISC 360 and the AISC Stainless Steel Design Guide

Members in Compression						
	Description of Element	Width-to-Thickness Ratio	Limiting Width-to-Thickness Ratio λ_r (nonslender / slender)			
			Carbon Steel	Stainless Steel		
Unstiffened Elements	Flanges of rolled I-shaped sections, plates projecting from rolled I-shaped sections	b/t	$0.56\sqrt{E/F_y}$	$0.47\sqrt{E/F_y}$		
	Flanges of built-up I-shaped sections and plates or angle legs projecting from built-up I-shaped sections	b/t	$0.64\sqrt{k_c E/F_y}$ where $k_c = \frac{4}{h/t_w}$	$0.47\sqrt{E/F_y}$		
	Legs of single angles, legs of double angles with separators, and all other unstiffened elements	b/t	$0.45\sqrt{E/F_y}$	$0.38\sqrt{E/F_y}$		
Stiffened Elements	Webs of doubly-symmetric I-shaped sections and channels	h/t_w	$1.49\sqrt{E/F_y}$	$1.24\sqrt{E/F_y}$		
	Walls of rectangular HSS and boxes of uniform thickness	b/t	$1.40\sqrt{E/F_y}$	$1.24\sqrt{E/F_y}$		
	All other stiffened elements	b/t	$1.49\sqrt{E/F_y}$	$1.24\sqrt{E/F_y}$		
	Round HSS	D/t	$0.11E/F_y$	$0.10E/F_y$		
Members in Flexure						
	Description of Element		λ_p (compact / noncompact)		λ_r (noncompact / slender)	
			Carbon Steel	Stainless Steel	Carbon Steel	Stainless Steel
Unstiffened Elements	Flanges of rolled I-shaped sections and channels	b/t	$0.38\sqrt{E/F_y}$	$0.33\sqrt{E/F_y}$	$1.0\sqrt{E/F_y}$	$0.47\sqrt{E/F_y}$
	Flanges of doubly and singly symmetric I-shaped built-up sections	b/t	$0.38\sqrt{E/F_y}$	$0.33\sqrt{E/F_y}$	$0.95\sqrt{k_c E/F_L}$	$0.47\sqrt{E/F_y}$
	Flanges of all I-shaped sections and channels in flexure about the weak axis	b/t	$0.38\sqrt{E/F_y}$	$0.33\sqrt{E/F_y}$	$1.0\sqrt{E/F_y}$	$0.47\sqrt{E/F_y}$
Stiffened Elements	Webs of doubly-symmetric I-shaped sections and channels	h/t_w	$3.76\sqrt{E/F_y}$	$2.54\sqrt{E/F_y}$	$5.70\sqrt{E/F_y}$	$3.01\sqrt{E/F_y}$
	Flanges of rectangular HSS and boxes of uniform thickness	b/t	$1.12\sqrt{E/F_y}$	$1.12\sqrt{E/F_y}$	$1.4\sqrt{E/F_y}$	$1.24\sqrt{E/F_y}$
	Webs of rectangular HSS and boxes	h/t	$2.42\sqrt{E/F_y}$	$2.42\sqrt{E/F_y}$	$5.70\sqrt{E/F_y}$	$3.01\sqrt{E/F_y}$
	Round HSS	D/t	$0.07E/F_y$	$0.07E/F_y$	$0.31E/F_y$	$0.31E/F_y$

5 Members in Compression

AISC 360 gives one flexural buckling curve which applies to all sections. In comparison, Eurocode 3 gives a choice of four buckling curves for carbon and three for stainless steel sections, depending on the axis of buckling, the height-to-width ratio of the cross-section, flange thickness, cross-section shape and method of manufacture.

Using test data for calibration, an AISC stainless steel buckling curve was derived which retained the format of the AISC carbon steel buckling expression, modifying the coefficients in the buckling expressions for carbon steel to suit the experimental stainless steel data. This is a different approach to that taken in SEI/ASCE 8, which takes the nonlinear stress-strain curve of stainless steel into account by replacing the initial elastic modulus with the tangent modulus

corresponding to the buckling stress; this involves an iterative design procedure. For the AISC Design Guide, as for the Eurocode, it was considered preferable to have an explicit design solution as opposed to one requiring an iterative solution.

The experimental data used to derive the curve included compression tests on rectangular HSS, round HSS and I-shaped members. Test data for this analysis were obtained from Young & Lui [19], Talja & Salmi [20], and Gardner and Nethercot [21] for rectangular HSS. Data for I-shaped members were found in Talja [22]. Data for round HSS sections were found in Talja [22], Young & Hartono [23], Way [24] and Rasmussen & Hancock [25].

The AISC stainless steel buckling curve is shown in Figure 9, with the experimental data used in the calibration. The figure also shows the equivalent expression for carbon steel, as given in AISC 360 Eq. E3-1 to E3-4 and the Eurocode stainless steel buckling curve for welded open sections, buckling about the minor axis. Table 4 gives the expressions for the buckling curves.

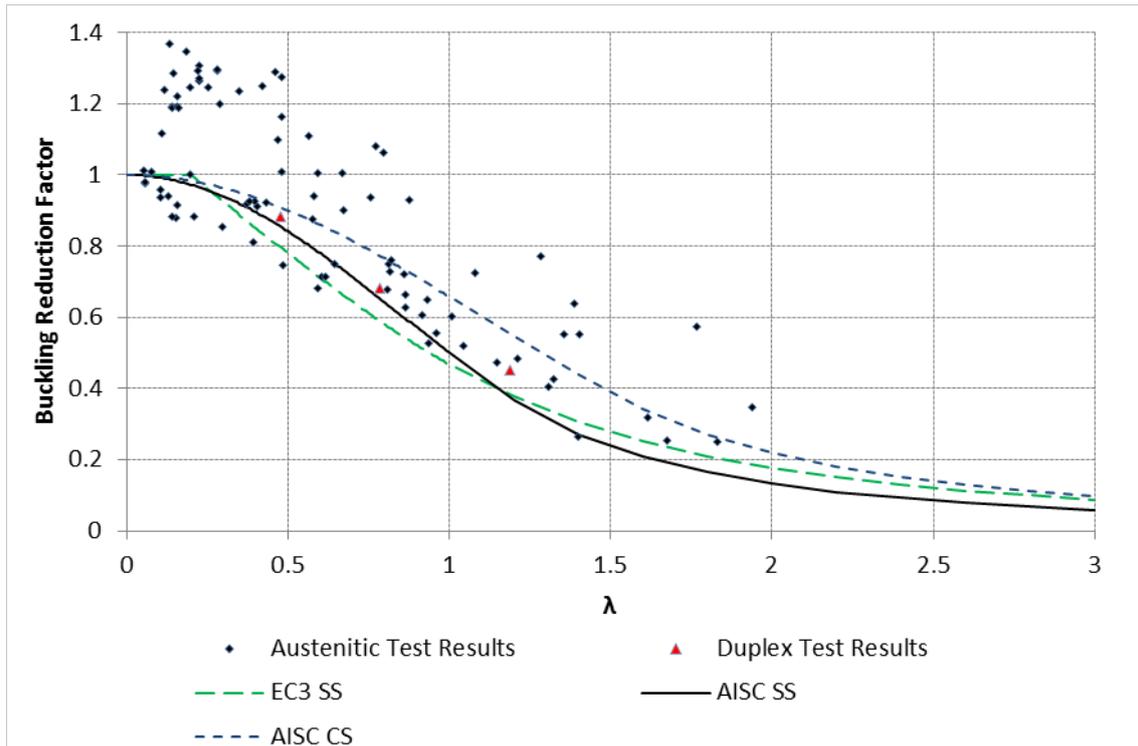


Fig. 9 Flexural buckling curves, plotted with stainless steel experimental results

Table 4 AISC Flexural buckling curves for carbon steel [3] and stainless steel [2]

Carbon Steel (AISC 360)	Stainless Steel (AISC Design Guide)
$\frac{F_y}{F_e} \leq 2.25, F_{cr} = \left[0.658 \frac{F_y}{F_e} \right] F_y$	$\frac{F_y}{F_e} \leq 1.44, F_{cr} = \left[0.500 \frac{F_y}{F_e} \right] F_y$
$\frac{F_y}{F_e} > 2.25, F_{cr} = 0.877 F_e$	$\frac{F_y}{F_e} > 1.44, F_{cr} = 0.531 F_e$
For carbon steel and stainless steel, $F_e = \frac{\pi^2 E}{\left(\frac{KL}{r} \right)^2}$	

In accordance with the procedure described in Section 3, a resistance factor $\phi_c = 0.960$ for flexural buckling was determined for all austenitic stainless steel compression members. The AISC carbon steel resistance factor for members in compression $\phi_c = 0.9$ appeared to be safe choice. However, for a significant proportion ($> 5\%$) of the round HSS tests, the predicted design strength $\phi_c P_n$ exceeded the measured strength. Since the predictions were based on the measured material properties and not the minimum specified material properties, it does not imply that the design model

was unconservative, but nevertheless it was considered to be undesirable to have more than one test point where $\phi_c P_n$ exceeded the measured compression strength.

In order not to penalise the entire range of section shapes in the study unnecessarily, round HSS were isolated into a separate population for the purposes of determining the resistance factor. For all austenitic section shapes apart from round HSS, the test data indicated values of $P_m = 1.39$ and $V_p = 0.288$, leading to a resistance factor ϕ_c of 1.044. A similar value was derived for duplex stainless steels. Figure 10 shows the ratio of measured to predicted compression strengths plotted against member slenderness, with no points falling below the $\phi_c = 0.9$. It was therefore considered appropriate to adopt a value of $\phi_c = 0.9$, which is the same as the value in AISC 360 for carbon steel members in compression.

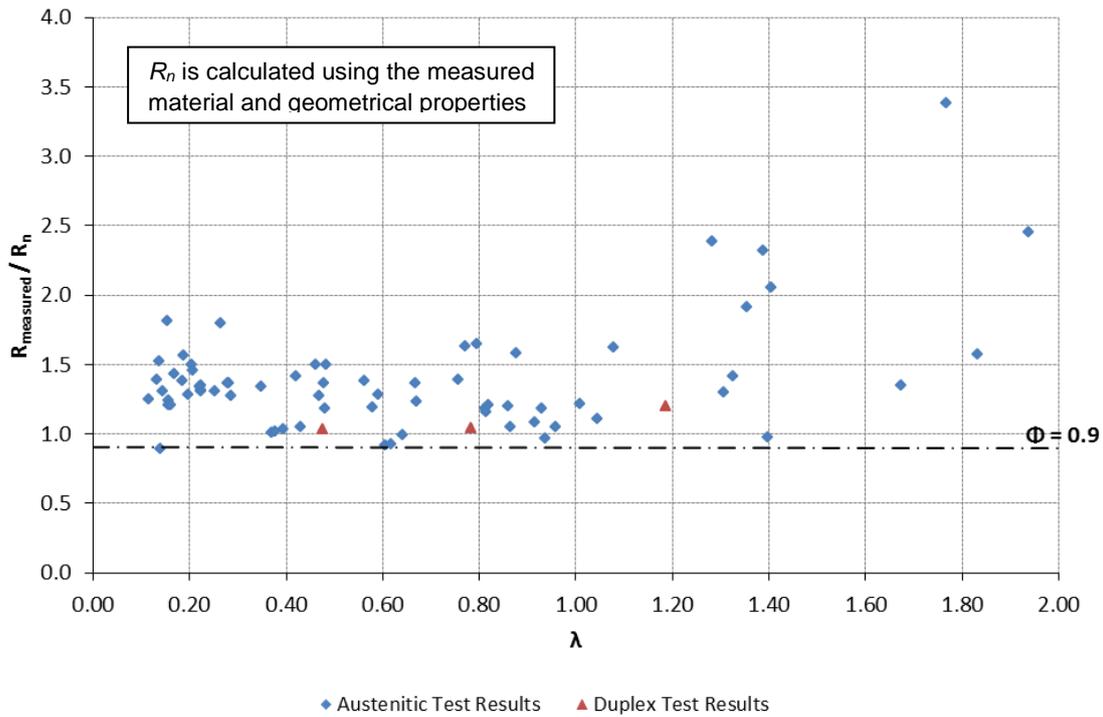


Fig. 10 Measured/predicted compression strengths against member slenderness (not including round HSS)

For austenitic stainless steel round HSS, test data indicate $P_m = 1.043$ and $V_p = 0.154$ with a resistance factor $\phi_c = 0.998$. Figure 11 shows the ratio of measured to predicted compression strengths for round HSS. With a value of $\phi_c = 0.85$, no points fall below the measured=predicted strength line; this value of ϕ_c was therefore adopted.

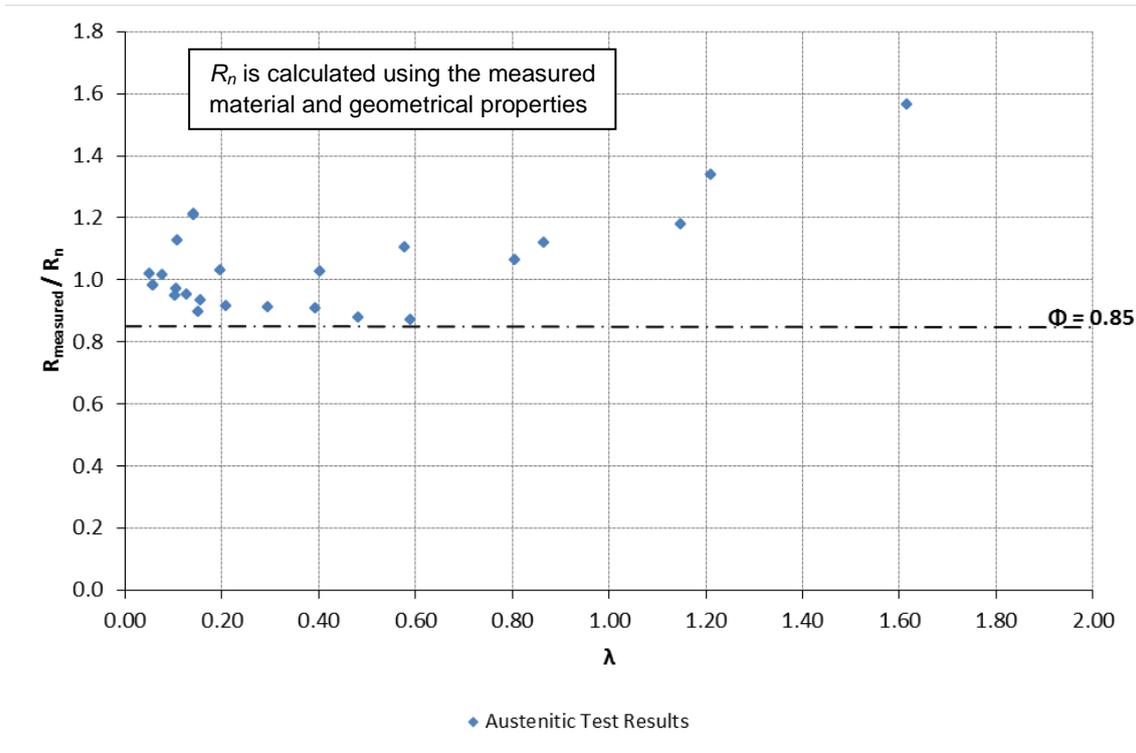


Fig. 11 Measured/predicted compression strengths against member slenderness for round HSS

6 Members in Bending

The strength expressions for carbon steel in AISC 360 for yielding and flange local buckling were shown to apply to stainless steel providing the stainless steel values of λ_p and λ_r are used (as given in Table 3 of this paper). For rectangular HSS, the AISC 360 expressions for flange and web local buckling were not given in terms of λ_p and λ_r , and therefore some coefficients required modification to suit the slightly different behaviour of stainless steel. A full reliability assessment of all cross-sections was carried out using data from tests on restrained beams and this indicated it was conservative to adopt the carbon steel value of $\phi_b = 0.9$.

The carbon steel AISC lateral torsional buckling curve is defined in three parts; L_p is the maximum unbraced length to reach M_p with uniform moment. Elastic lateral torsional buckling occurs when the unbraced length exceeds L_r . The middle part of the curve is a straight line representing inelastic lateral torsional buckling between L_p and L_r . It was necessary to modify the AISC expressions F2-2, F2-3 and F2-5 for doubly symmetric I-shaped members and channels with compact webs in order to generate a lower design curve close to the stainless steel test data. Equivalent modifications were made to the corresponding expressions for other I-shaped members with compact or non-compact webs. Figure 12 shows the AISC stainless steel modified lateral torsional buckling curve with the Eurocode stainless steel curve for welded sections and the AISC curve for carbon steel. The horizontal axis is the member slenderness for lateral torsional buckling, defined in EN 1993-1-4. The AISC carbon and stainless steel expressions are shown in Table 5.

Test data for this analysis was obtained from Stangenberg [26] and van Wyk et al [27]. By comparing the design model with test data a value of $P_m = 1.261$ and $V_p = 0.191$ was calculated for austenitic stainless steel, with a resistance factor of 1.139. For duplex stainless steel, similar values were derived. It was considered appropriate to adopt a value of $\phi_b = 0.9$, which is the same as the value in AISC 360 for carbon steel members subject to lateral torsional buckling.

Figure 13 shows the ratio of measured to predicted strengths against lateral torsional buckling slenderness for laterally unrestrained members against lateral torsional buckling slenderness. One test point falls beneath the $\phi_b = 0.9$ line, which is considered to be acceptable.

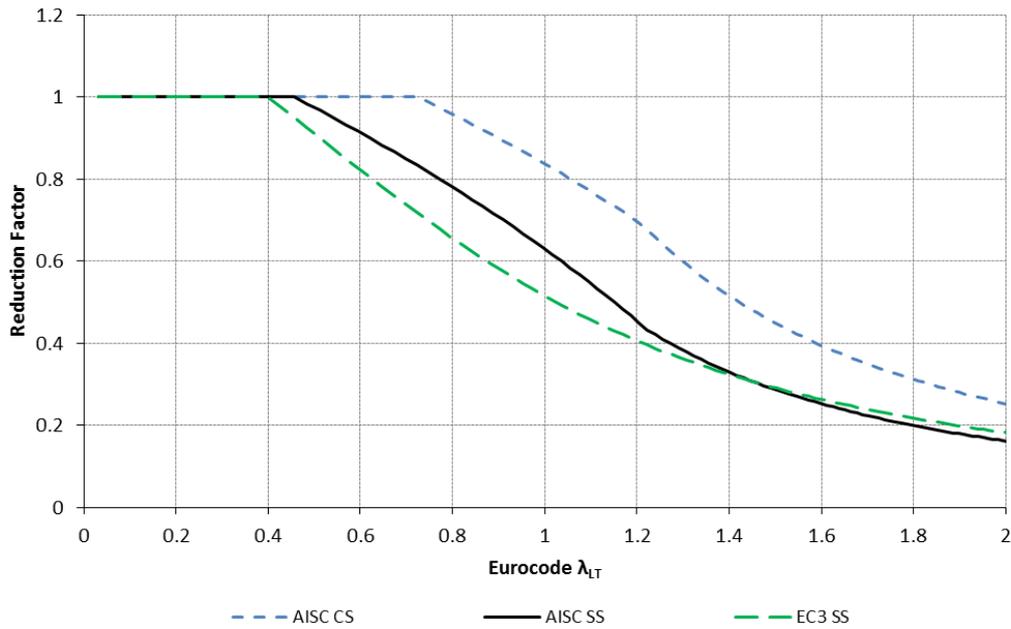


Fig. 12 Lateral torsional buckling curves

Table 5 AISC Lateral torsional buckling curves for carbon steel [3] and stainless steel [2]

Carbon Steel (AISC 360)	Stainless Steel (AISC Design Guide)
For $L_p < L_b \leq L_r$, $M_n = C_b \left[M_p - (M_p - 0.7F_y S_x) \left(\frac{L_b - L_p}{L_r - L_p} \right) \right] \leq M_p$	For $L_p < L_b \leq L_r$, $M_n = C_b \left[M_p - (M_p - 0.45F_y S_x) \left(\frac{L_b - L_p}{L_r - L_p} \right) \right] \leq M_p$
For $L_b > L_r$, $M_n = F_{cr} S_x \leq M_p$	For $L_b > L_r$, $M_n = 0.64F_{cr} S_x \leq M_p$
And $L_p = 1.76r_y \sqrt{\frac{E}{F_y}}$	And $L_p = 0.8r_y \sqrt{\frac{E}{F_y}}$

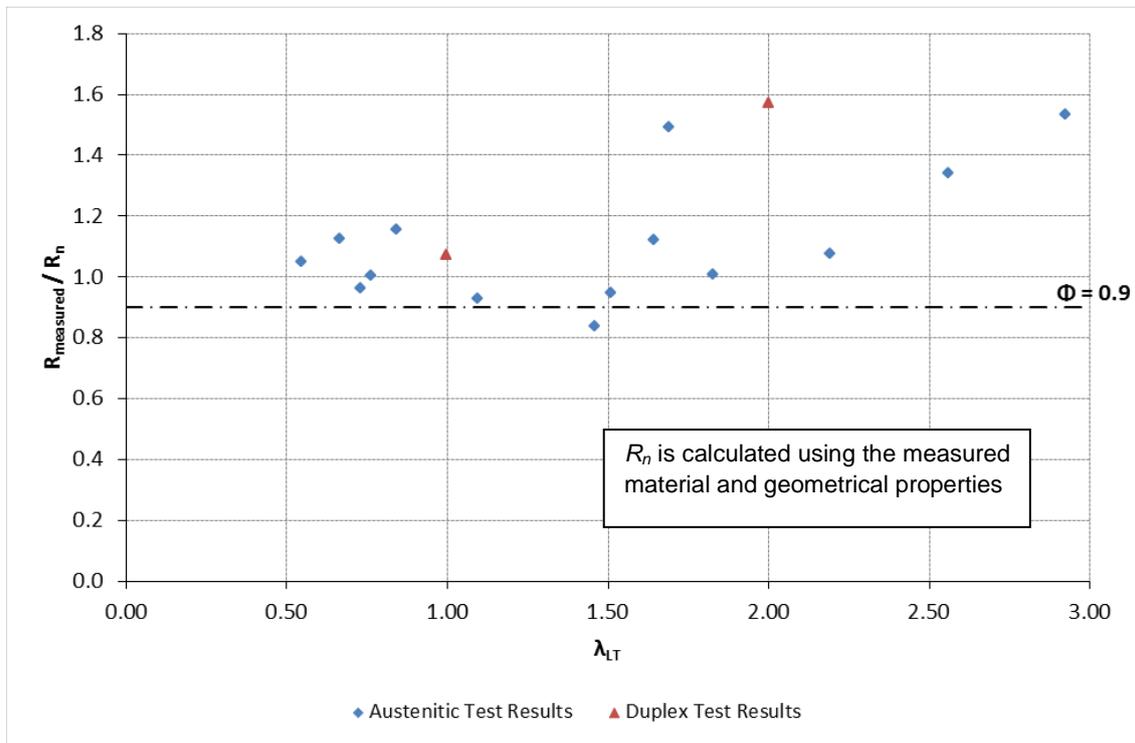


Fig. 13 Measured/predicted strengths for laterally unrestrained members against slenderness

7 Conclusions

Design rules for hot rolled and welded structural stainless steel have been derived which align with AISC 360 *Specification for Structural Steel Buildings*. The rules will be published in a new AISC Design Guide: *Structural Stainless Steel* in 2013. Where stainless steel behaves in a similar way to carbon steel, the Design Guide simply refers to the relevant section in AISC 360. For section classification, flexural and lateral torsional buckling, specific rules for stainless steel were derived and presented in a format as close as possible to the equivalent expressions in AISC 360. The stainless steel design rules were calibrated against an extensive database of test results on structural members and connections. A full reliability analysis was carried out to calculate the LRFD resistance factors; in most cases, the carbon steel resistance factors were shown to be applicable to stainless steel also.

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