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Design Criteria for Stainless-steel Structural Members

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In 1991, the research work jointly undertaken over the past six years by the Rand Afrikaans University and the University of Missouri–Rolla, USA, resulted in the publication by the American Society of Civil Engineers of a specification for the design of cold-formed stainless-steel structural members and connections. The specification contains both the Allowable Stress Design Method and the Load and Resistance Factor Design Method or the Limit State Method. This paper gives a brief historical review of the relevant research, compares the differences between designing in stainless steels, and in carbon and low-alloy steels, and discusses current and planned future activities.

Historical Review

Recognizing the difference between the mechanical behaviour of stainless steels and that of carbon and low-alloy steels, a research programme sponsored by the American Iron and Steel Institute (AISI) was started at Cornell University in the USA during the early 1960's. The object of this programme was to develop criteria for the design of structural members cold-formed from stainless steels. Based on research conducted by Johnson[1] under the direction of George Winter, and on the experience gained from research and design in carbon and low-alloy steels over a period of thirty years, a specification for the design of light-gauge cold-formed stainless-steel members[2] was issued in 1968. This specification covered six austenitic stainless steels in the annealed and strain-flattened condition.

Subsequent research data generated by Wang and Errera[3-4], and also by Errera, Tang, and Popowich[5], again under the direction of Winter at Cornell University, was compiled to form the second edition, the 1974 edition[6], by Yu at the University of Missouri-Rolla, USA. The manual contains four parts. Part I is the design specification and Part II is a commentary. Design examples are given in Part III, and tables and charts, useful for the determination of safe load-carrying capacities and deflections of member sections, are to be found in Part IV. The six types of austenitic stainless steels covered by the specification[6] are AISI types 201, 202, 301, 302, 304, and 316 in four strength levels, grades A, B, C, and D, in accordance with ASTM designation A666-72[7].

The requirements[7] of ASTM A666-72 have to be strictly adhered to. Other types of austenitic stainless steels or other types of stainless steels, such as ferritic or martensitic stainless steels, may no longer be regarded as suitable materials in accordance with the design specification[6].

Since the 1974 specification[6] on stainless steel design lacked a considerable amount of design provisions in comparison with the design specification for carbon and low-alloy steels, a research programme, sponsored mainly by Chromium Centre (International Chromium Development Association) and the Nickel Development Institute, was started at the Rand Afrikaans University and the University of Missouri–Rolla in the mid 1980's with the object of updating the 1974 edition of the design specification for stainless-steel structures[6] and of expanding on the types of stainless steels for which design criteria are known.

Based on the work by Van der Merwe[8], Van den Berg[9], and Lin[10], prepared under the supervision of Wei-Wen Yu, the American Society of Civil Engineers issued ASCE standard 8–90[11] in 1991. This document contains both the Allowable Stress Design Method and the Load and Resistance Factor Design Method, and is written in the same format as its counterpart on carbon and low-alloy steels[8]. It also contains criteria for the design of structures using ferritic stainless steels. The range of steels covered are four AISI austenitic stainless steels types 201, 301, 304, and 316, as well as three AISI ferritic stainless steels, types 409, 430, and 439.

Should any stainless steel other than those listed in the design specification[11] be considered for structural applications, an in-depth study of its stress–strain behaviour would be the minimum required research to be undertaken to determine the mechanical properties, followed preferably by tests on structural members.

Stress–Strain Behaviour of Stainless Steels

Owing to the differences in the stress-strain behaviour between stainless steels and carbon and low-alloy steels, the various design specifications covering the design of structural members made of carbon and low-alloy steel do not apply to the stainless-steel structural members. In addition to the difference in the shape of the stress–strain curves[3], stainless steels have four distinctive stress–strain curves for longitudinal tension and compression, and for transverse tension and compression. Other differences are the strong effect of cold-working in increasing the strength, and the low proportional limit, especially in compression[12].

Non-linear Stress–Strain Relationships

For carbon and low-alloy steels, a single stress-strain curve of the sharp-yielding type (for virgin material) is assumed to be valid for tension and compression. In contrast to this, stainless steels are categorized as having gradually yielding stress–strain behaviour. Aspects that should be considered include the proportional limit, F_p, which could be considerably lower than the yield strength, F_y; moduli such as the initial modulus, E_o (defined as the slope of the initial part of the stress–strain curve), the tangent modulus, E_t (defined as the slope of the tangent to the stress–strain curve at each value of stress), and the secant modulus, E_s (defined as the ratio of the stress to the strain at each value of stress); and other moduli, such as the tangent shear modulus (defined as the tangent to the shear stress–shear strain curve) and the secant modulus (defined as the ratio of the shear stress to the shear strain at each value of stress). Figure 1 identifies a number of these properties.

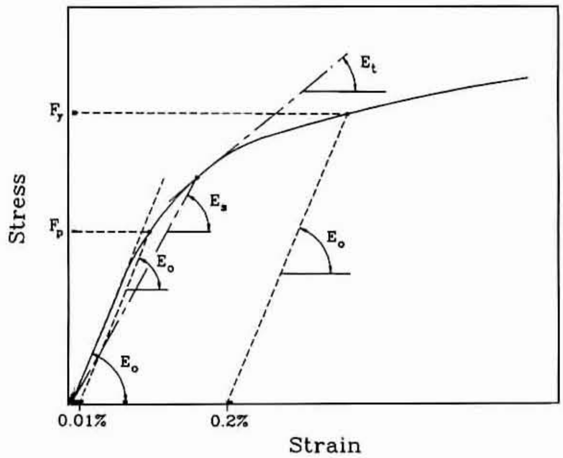

FIGURE 1. Typical stress–strain behaviour of a stainless steel

Figure 2 shows a typical stress–strain curve for type 304 stainless steel, reproduced from tensile test data generated at the Rand Afrikaans University. It should be noted that the first 0,005 strain portion is the portion of the curve most useful for the design of structural members.

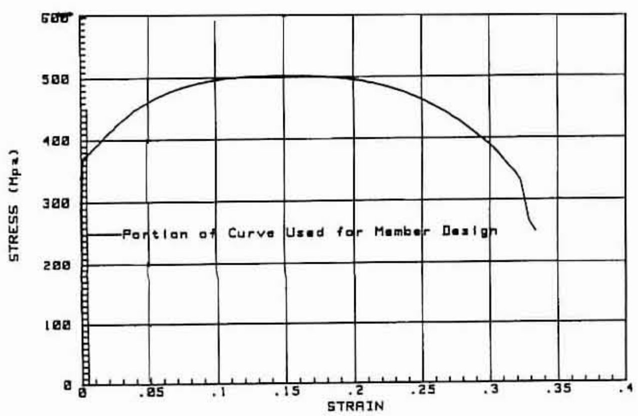

FIGURE 2. Typical complete stress–strain curve for a stainless steel

Anisotropy

Four stress–strain curves are required for the identification of the stress–strain behaviour of a stainless steel. The curves are those for longitudinal tension (LT), longitudinal compression (LC), transverse tension (TT), and transverse compression (TC). The term *longitudinal* refers to the direction parallel to the direction of rolling of a flat plate, sheet, strip, or flat bar, and the term *transverse* refers to the direction perpendicular to the direction of rolling.

The four curves shown in Figure 3 are also for type 304 stainless steel.

The absence of sharp yielding should be noted. The horizontal axis has been expanded (compared with Figure 2) to make the useful portion of the curve visible for interpretation.

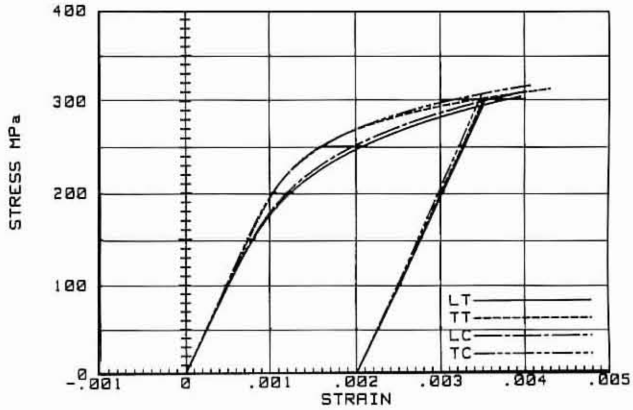

FIGURE 3. A set of stress–strain curves for a stainless steel

Low Proportional Limit

The stress–strain curves for stainless steels are always of the gradual yielding type accompanied by relatively low proportional limits, especially in longitudinal compression. The proportional limit is defined as the 0,01 per cent offset strength value. The design equations for carbon and low-alloy steels are based on the assumption that the proportional limits of the various grades of steel are at least 70 per cent of the yield point or yield stress. For stainless steels, the proportional limits range from approximately 35 to 80 per cent of the yield strength depending on the type of stainless steel and on the sense and direction of stressing.

Lower proportional limits affect the buckling behaviour, and hence the strength of structural members and components.

Pronounced Response to Cold Work

Properties such as the yield strength and ultimate strength of austenitic stainless steels can be enhanced by as much as 246 per cent if the thickness of the plate, sheet, strip, or flat bar is reduced by cold-rolling[7]. Strength properties are also increased in the vicinity of corners of cold-formed member sections.

Differences in Design

The design of cold-formed stainless steel is similar to that of cold-formed carbon steel. However, since the mechanical properties of stainless steels are more complex than those of carbon steels, the design procedures for the former are occasionally more involved.

In order to account for the different response to load between stainless steels and carbon and low-alloy steels, certain modifications to the design equations are needed for the following aspects:

- inelastic buckling of flat elements subjected to compression, shear, or bending
- local distortions
- safety and resistance factors
- determination of deflections
- anisotropy lateral torsional buckling of beams
- flexural and torsional flexural buckling of columns
- limitation of width-to-thickness ratios.

Inelastic Buckling of Flat Elements

Owing to the relatively low values of the proportional limit of stainless steels, flat elements subjected to compression, shear, or bending may buckle at stresses that exceed the proportional limit, hence inelastic buckling. Plasticity reduction factors are being used to modify the design equations that have been derived for elastic buckling. These are listed in Table I.

TABLE I
PLASTICITY REDUCTION FACTORS FOR INELASTIC BUCKLING OF FLAT ELEMENTS.

Type of buckling stress	Plasticity reduction factor
Compression	
Unstiffened elements	E_s/E_o
Stiffened elements	$\sqrt{E_t/E_o}$
Shear	G_s/G_o
Bending	E_s/E_o

G_o = Shear modulus
G_s= Secant shear modulus

Local Distortions

When local distortions in flexural members under nominal service loads must be limited, the design flexural strength is determined at a stress equal to the critical local buckling stress, multiplied by a factor that depends on the amount of distortion that is allowed. Normally, this factor will vary[12] between 0,75 and 1,2. The plasticity reduction factor for inelastic buckling for compression given in Table I is used to determine the critical local buckling strength.

Safety and Resistance Factors

Owing to the lack of design experience and the lack of sufficient test data for statistical analysis, relatively large safety factors and resistance factors are found in design specifications for stainless steels.

Determination of Deflections

A reduced modulus $E_r = (E_{ts}+E_{cs})/2$ is stipulated for the calculation of deflections. In this equation, E_{ts} is the secant modulus corresponding to the stress in the tension flange, and E_{cs} is the secant modulus corresponding to the stress in the compression flange. The different response of the material to tension and compression is accounted for by this reduced modulus, as well as by the likelihood that the stress under service load in the extreme fibre may be higher than the proportional limit.

Anisotropy

Since four stress–strain curves are needed to describe the stress–strain behaviour of a stainless steel, care should be taken in the selection of the values of properties and plasticity-reduction factors for design purposes. The longitudinal axes of structural members will normally coincide with the longitudinal direction as defined earlier.

Lateral Torsional Buckling of Beams

For inelastic lateral torsional buckling, the stainless-steel design specification[11] requires the use of a plasticity reduction factor based on the tangent modulus approach in conjunction with the equation that would otherwise be used for elastic behaviour in carbon and low-alloy steels. The parabolic equation used in the design specification[13] for inelastic buckling in carbon and low-alloy steel cannot be used for stainless-steel design. This effect is illustrated in Figure 4.

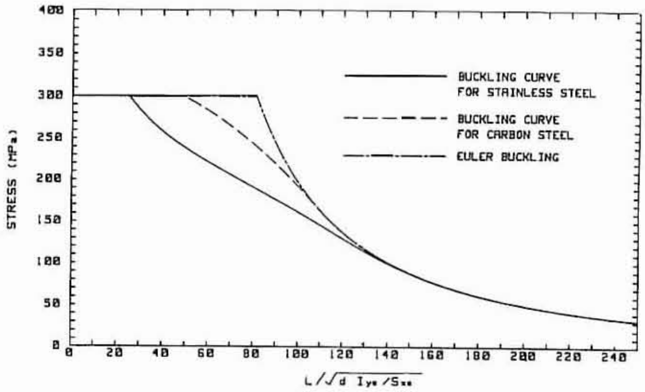

FIGURE 4. Lateral buckling of beams

Flexural and Torsional Flexural Buckling of Columns

For the same reasons as mentioned above, the tangent modulus theory for column buckling is used to predict the failure of axially loaded compact compression members. Figure 5 shows the difference between the design approaches for a carbon steel and a stainless steel with identical yield-strength values against the Euler buckling curve.

Limitations of Width-to-Thickness Ratios

Where pleasing appearance is of importance, the width-to-thickness ratio of flat elements has to be reduced to minimize local distortion of the elements. These ratios for stainless steel are different from those for carbon and low-alloy steels.

Future Activities

An organization is being set up that will introduce the new ASCE design specification to engineers and engineering students through short courses and seminars on a world-wide basis. Computer software has been developed at the

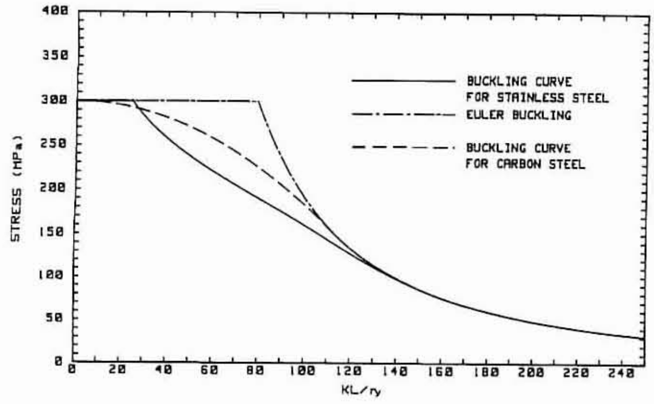

FIGURE 5. Column buckling

Rand Afrikaans University, and thought is being given to the provision of a design consultancy service.

The information available in the new ASCE specification[11] is an improvement on that in the 1974 edition[6]. However, it still lacks information when compared with its counterpart on carbon and low-alloy steels[6]. Research is in progress to address these deficiencies. The range of steels covered by the ASCE design specification has to be increased. At the Rand Afrikaans University, some exploratory work has been done on the potential of chromium–manganese steels for structural applications. Type 205 steel appears to be suitable. Work is already in progress on updating the ASCE design specification, the next edition being due in 1996. The ASCE design specification is in the format familiar in the USA, and format translations are being undertaken to serve the needs of other countries.

Heavy hot-rolled sections are becoming increasingly available from Japanese mills. This opens a whole new field for structural-steel research aimed at generating the information required for safe and durable steel structures.

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