Gardner, L. (2005). The use of stainless steel in structures. Progress in Structural Engineering and Materials. **7(2)**, 45-55.

The use of stainless steel in structures

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Summary

The past fifteen years have seen the introduction or major revision of structural stainless steel design codes throughout the world, and at the same time, interest in the use of stainless steel in construction has been accelerating. Historically the high initial material cost of stainless steel has limited its use primarily to specialist and prestige applications. However, the emergence of design codes, a better awareness of the additional benefits of stainless steel and a transition towards sustainability are bringing more widespread use into conventional structures. Although a number of similarities between stainless steel and ordinary carbon steel exist, there is sufficient diversity in their physical properties to require separate treatment in structural design. In addition to the straightforward differences in basic material properties (such as Young's modulus and yield strength), further fundamental differences exist, such as the nature of the stress-strain curve and the material's response to cold-work and elevated temperatures; these have implications at ultimate, serviceability and fire limit states. This paper describes the use of stainless steel as a structural material, discusses current structural design provisions, reviews recent research activities and highlights the important findings and developments.

Keywords

Stainless steel, structural engineering, Eurocode 3, corrosion resistance, material modelling, cross-section design, member design

Introduction

Stainless steel has traditionally been regarded as an extravagant solution to structural engineering problems. Consequently, the use of stainless steel as a primary structural material for conventional construction remains rather limited. Previously, coupled with the high initial material costs, there have been a number of disincentives to adopt stainless steel, including limited structural design guidance, restricted section availability (and no standardisation) and a lack of understanding of the additional benefits of stainless steel amongst structural engineers. Since the last significant general review of the use of stainless steel in structures [1], carried out in 1993, there have been considerable advancements. These are described throughout this paper.

Historical background

For the past eighty years the longevity and aesthetic appeal of stainless steel has inspired architects and designers alike to use the material in both practical and imaginative ways. Stainless steel was first introduced in 1912-1913 (by Brearley in the UK and Maurer and Strauss in Germany). Brearley referred to the material as ‘rustless steel’ and it was a cutlery manager, Ernest Stuart, who popularised the term ‘stainless’. Stainless steel is now used as a general expression to describe corrosion resistant iron alloys that contain a minimum of 10.5% chromium. A thorough account of the initiation and growth of stainless steel production is given by Truman [2].

Chemical composition and material grades

As with carbon steel, there is a wide variety of grades of stainless steel, generated through variation in chemical composition and heat treatment. These may be classified into five main groups according to their metallurgical structure, namely austenitic, ferritic, duplex (austenitic-ferritic), matensitic and precipitation hardening. In addition to the minimum of 10.5% chromium (Cr) required to give stainless steel its corrosion resistance, a number of other alloying elements may be present. These include carbon (C), nickel (Ni), manganese (Mn), molybdenum (Mo), copper (Cu), silicon (Si), sulphur (S), phosphorus (P) and nitrogen (N). The chemical compositions (% by mass of alloying elements) associated with the different grades are defined in [3].

The most common grades for structural applications are the austenitic and duplex grades. These will be discussed in more detail. Austenitic stainless steels typically contain 17-18% chromium and 8-11% nickel, offer very good corrosion resistance and have an austenitic microstructure. Duplex stainless steels typically contain 22-23% chromium and 4-5% nickel and have a mixed austenitic-ferritic microstructure. The duplex stainless steels offer higher strength, wear resistance and generally corrosion resistance than the austenitics, but at greater expense.

In addition to the high number of grades of stainless steel, there are also a number of different stainless steel designation systems. The system adopted in the remainder of this paper will be that given in the European material Standard, EN 10088-1 [3]. For each standard stainless steel grade, EN 10088-1 defines a steel name and a steel number. It is the steel number that will be referred to herein. Equivalent designations, including those to the German (DIN) and the US (AISI) systems are provided in [4].

Chemical compositions for three grades of stainless steel commonly adopted in structures, two austenitic, EN 1.4301 and EN 1.4401 and one duplex, EN 1.4462 are provided in Table 1. Equivalent designations for grades EN 1.4301, EN 1.4401, EN 1.4462 according to the popular AISI system are AISI 304, 316 and 2205, respectively. Further information relating to stainless steel material properties and material selection is available [1, 5, 6].

Structural products

Stainless steel product forms include plate, sheet, strip, tube, bar, cold-formed and hot-rolled structural sections, castings, fasteners and fixings. For structural members, the most commonly used products are cold-formed sections, predominantly because these are the most readily available, require relatively low investment to achieve production capabilities, and are suitable for light structural applications with high structural (and material) efficiency. Hot-rolled and built-up sections are relatively scarce, though structural design guidance is available, as described later in this paper.

Essentially cold-formed sections may be formed from flat sheet either by press-braking or roll-forming; press-braking is generally limited to simple shapes and low production levels and is often used for prototyping, whereas roll-forming is suitable for larger quantities. Due to the material's response to cold-work, the strength of cold-formed structural stainless steel sections can be considerably enhanced during the forming process. These enhancements may arise during the production of the flat sheet or during the formation of the final cross-section. Strength enhancements in the sheet material may be utilised in design, with material strengths provided on the basis of the level of cold-work that the sheet receives. Strength enhancements during the cold-forming of the cross-sections are not included in existing design methods because there are currently no tools to determine the level and distribution of these enhancements for the particular process routes. Progress on the development of such tools is underway at Imperial College London.

There are also currently no standard sizes for stainless steel sections, with sections often made to order. However, most suppliers stock commonly requested section sizes, and geometric properties and member capacities for such sections have been tabulated based on British [7, 8] and European [9] rules.

Stress-strain behaviour

The stress-strain behaviour of stainless steel is fundamentally different from that of carbon steel, as indicated by Figure 1. Whereas carbon steel exhibits a sharply defined yield point, followed by a flat yield plateau and then some strain hardening, stainless steel displays a rounded stress-strain curve, with no sharp yield point, considerable strain hardening and high ductility. For the common austenitic stainless steel grades, the ductility (strain at fracture) is approximately 40-60%, as compared to around 20-30% for carbon steel.

The absence of a sharply defined yield point necessitates the definition of an 'equivalent' yield point for design; the generally accepted approach is to adopt the stress at 0.2% plastic strain (i.e. the 0.2% proof stress), as shown in Figure 2.

The degree of roundedness of the stress-strain curve of stainless steel depends on the grade (i.e. the chemical composition and heat treatment) and the level of cold-work that the material has been subjected to. Annealed material has a sharper yield point followed by approximately linear strain hardening, whereas cold-worked material displays higher strength and more rounded stress-strain behaviour (see Figure 3). Stainless steel also exhibits anisotropy and non-symmetry of stress-strain behaviour in tension and compression (defining four stress-strain curves). Both of these effects become more pronounced as the level of cold-work increases. For example, for the common austenitic grades in the annealed condition, variation in 0.2% proof stress between the four stress-strain curves is less than 5%, but for cold-worked material this can increase to around 20%. Most material Standards provide tension and compression stress-strain properties in both the longitudinal and transverse directions, thus enabling the effects of anisotropy and non-symmetry to be recognised in design. However, numerical studies have indicated that the behaviour of common structural elements (compressed plates) is relatively insensitive to material anisotropy [10] and, for simplicity or conservatism under complex loading systems, the minimum material properties can be adopted.

For both design and numerical simulation, carbon steel material behaviour is often represented with a bi-linear (elastic, perfectly-plastic) relationship. Although carbon steel does display some deviation for this idealised model (e.g. strain hardening beyond approximately 1.5% strain), for the majority of applications the model is acceptable. However, for stainless steel the bi-linear model is less satisfactory, and indeed direct use would generally lead to overly conservative design at ultimate limit state and under-prediction of deflections at serviceability limit state. Hence, a number of more accurate material models have been proposed.

The most commonly adopted expression, originally proposed by Ramberg and Osgood [11] and modified by Hill [12], is given by Equation 1.

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \quad (1)$$

where σ and ε are engineering stress and strain, respectively, E_0 is the material Young's modulus, $\sigma_{0.2}$ is the material 0.2% proof stress and n is a strain hardening exponent. A review of other material models and investigation into their applicability to stainless steels was made in 2002 [13].

Deviation of the basic Ramberg-Osgood expression from experimental stress-strain data at higher strains has been observed by a number of authors [14, 15, 16]. A modification to the basic Ramberg-Osgood expression was proposed by Mirambell and Real [14] whereby the single curve defined by Equation 1 was replaced by a two-stage model, incorporating two Ramberg-Osgood curves. In their proposed model, the basic Ramberg-Osgood expression was adopted up to the 0.2% proof stress.

Beyond the 0.2% proof stress and up to ultimate stress, a second Ramberg-Osgood curve was used. The origin of the second curve was defined at the 0.2% proof stress, and continuity of magnitude and gradient was ensured at the transition point. Further work on this two-stage model was conducted [16] where the additional parameters required by the two-stage model were described in terms of the original Ramberg-Osgood parameters ($\sigma_{0.2}$, E_0 and n) following analysis of stainless steel stress-strain data.

Gardner and Nethercot [17] recognized the value of the Mirambell and Real proposal, but noted that use of the ultimate stress, σ_u in the second phase of the model (between $\sigma_{0.2}$ and σ_u) has two drawbacks. Firstly, since the strain at σ_u is far higher than those strains concurrent with general structural response, greater deviation between measured and modelled material behaviour results than if a lower strain was used. Secondly, and more importantly, the model is not applicable to compressive stress-strain behaviour, since there is no ultimate stress in compression, due to the absence of the necking phenomenon.

Use of the 1% proof stress in place of the ultimate stress was therefore proposed [17], leading to Equation 2. Equation 1 remains applicable for stresses up to $\sigma_{0.2}$.

$$\varepsilon = \frac{(\sigma - \sigma_{0.2})}{E_{0.2}} + \left(0.008 - \frac{\sigma_{1.0} - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}}\right)^{n'_{0.2,1.0}} + \varepsilon_{t0.2} \qquad (\sigma \geq \sigma_{0.2}) \qquad (2)$$

where $n'_{0.2,\,1.0}$ is a strain hardening coefficient representing a curve that passes through $\sigma_{0.2}$ and $\sigma_{1.0}$.

Equation 2 provides excellent agreement with experimental stress-strain data, both in compression and tension, up to strains of approximately 10%, and is therefore appropriate for design and numerical modelling. Where higher strains are expected, the original proposal of [14] is most appropriate.

Corner material properties

The stress-strain properties of the corner regions of cold-formed stainless steel cross-sections differ from those of the flat regions due to the material's response to deformation. Enhancements in 0.2% proof strengths of between 20% and 100% have been observed, accompanied by a corresponding loss in ductility.

A careful review of the corner properties of cold-formed stainless steel sections has been conducted [18]. On the basis of test results from press-braked [19, 20] and roll-formed [13, 21, 22] sections, models for the prediction of corner strength enhancements were proposed.

Corrosion resistance

An important feature of stainless steel is its corrosion resistance, enabling its application, unprotected, in a wide range of environments. The corrosion resistance of stainless steel is primarily attributable to its chromium content, though other alloying elements (including nickel and molybdenum) also contribute. On exposure to oxygen, the chromium in the steel reacts to form a thin, chromium-rich, oxide film over the surface of the material. It is the presence of this passive film that provides the resistance to corrosion. There are a number of different forms of corrosion including, general (uniform), abrasive, pitting, crevice, intergranular and galvanic corrosion. An account of the susceptibility of stainless steel to each of these is given in [5]. It should be noted that certain environments, such as those containing high concentrations of chlorides, can be extremely detrimental to the corrosion resistance and resistance to stress-corrosion cracking of stainless steels. In such cases, care must be taken to select suitable grades and it is recommended that specialist advice is sought. Detailed guidance may be found in [23].

Factors influencing material choice

In addition to structural performance, there are a number of other issues that influence the choice of material in construction, and although stainless steel has a high initial material cost, it possesses additional beneficial properties that may provide cost savings elsewhere. Factors influencing stainless steel as a material choice for use in structures is discussed in this section.

Cost

The initial cost of stainless steel structural products is about four times that of equivalent carbon steel products, owing largely to the expense of the alloying elements and the relatively low levels of production. Although this deficit is likely to reduce with increased production of structural stainless steel components and more efficient design rules, a considerable disparity remains. However, there are a number of other issues that should be included for a 'true' comparison of costs. These are discussed in the following sub-sections.

Aesthetics

Historically, the aesthetics of stainless steel has been an important factor in its specification for structural applications. Consequently, many existing examples of stainless steel structures [6] display a high level of exposed structural members, commonly of tubular cross-section, and are often of a prestigious or landmark nature. Its appeal is principally due to the surface finish and its ability to retain its appearance without deterioration over time. The appearance and longevity of the material is exemplified by the upper facade of the Chrysler Building in New York (completed in 1936), which despite the aggressive atmosphere and proximity to the ocean, remains bright and clean.

Durability

The corrosion resistance of stainless steels make them one of the most durable families of construction materials. With appropriate selection of material grade and structural design and only a minimum of maintenance, design lives well in excess of 100 years can be achieved. Also, with no requirement for protective coatings against corrosion, there are savings in terms of economy, weight and reduction in environmental impact.

Elevated temperature behaviour

At elevated temperatures, stainless steel offers better retention of strength and stiffness than carbon steel, due to the beneficial effects of the alloying elements. A comparison of the elevated temperature performance of austenitic stainless steel and carbon steel is given in Figures 4 and 5, where $f_y(\theta)$ and $E(\theta)$ refer to the nominal yield strength and stiffness, respectively, at temperature θ, and $f_y(20°C)$ and $E(20°C)$ refer to the nominal yield strength and stiffness, respectively, at room temperature. The data for these graphs have been taken from the Euro Inox *Design Manual for Structural Stainless Steel* [5], though were originally generated by [24], and are expected to be included in EN 1993-1-2 (when it is converted from its current ENV status). The graphs demonstrate the superior elevated temperature material properties of stainless steel, particularly in the important temperature region (~ 600 to 800°C) that generally corresponds to approximately 30 minutes fire resistance; for example, at 800°C the strength retention, $f_y(\theta)/f_y(20°C)$ of stainless steel is almost 4 times that of carbon steel and the stiffness retention, $E(\theta)/E(20°C)$ is 7 times that of carbon steel. A number of studies are currently underway to further investigate the behaviour of stainless steel structures in fire.

It may also be observed from Figure 4 that at low temperatures stainless steel has a strength reduction factor greater than unity. This is possible, because at fire limit state where higher deformations may be tolerated, ‘yield’ strength is defined at 2% strain (rather than the 0.2% proof strain adopted at ambient temperatures), and thus, the substantial strain hardening that stainless steel exhibits is utilised.

The resistance of structural stainless steel members in fire has been investigated experimentally [25, 26] and shown to perform better than equivalent carbon steel members. This enhanced fire resistance may reduce or even eliminate the need for protective fire coatings to be applied to structural members [25].

In addition to the important differences in the ability of stainless steel and carbon steel to retain strength and stiffness at elevated temperatures, there is also variation in other thermal properties, including specific heat, emissivity and thermal expansion. The specific heat of stainless steel is approximately 500 J/kgK as compared to carbon steel which has a value of approximately 600J/kgK. The lower the specific heat of a material, the more rapidly it tends to heat up. However, stainless steel also has a lower emissivity than carbon steel (approximately 0.4 compared to 0.5). Emissivity is a dimensionless property that ranges between zero and unity, where zero corresponds to all radiation being reflected by a surface and unity corresponds to all radiation being absorbed, and therefore, the lower the emissivity, the more slowly the material heats up. Studies [26] have shown that these two factors (lower specific heat and lower emissivity) appear essentially to cancel each other out, resulting in stainless steel heating up at a very similar rate to carbon steel. The coefficient of thermal expansion of stainless steel is approximately 50% larger than that of carbon steel, which may result in additional loads being induced into structural elements due to restraint from other (stiffer) parts of the structure.

Ductility and impact resistance

Stainless steels, particularly the austenitic grades, offer very high ductility and impact resistance. It is therefore particularly suited to applications where ductility and impact resistance are important, such as offshore structures, crash barriers and structures susceptible to blast loading [27], and has already been applied to railway carriage construction. A study into the suitability of adopting stainless steel for structural frames in seismic regions has also been carried out [28], where it was concluded that stainless steel is a viable alternative to carbon steel, but further investigation is required. The level of ductility of stainless steel depends upon the material composition and heat treatment and on the degree of cold-work that the section has been subjected to, with reduced ductility for increasing cold-work.

Re-use and recycling

The construction industry is a major producer of waste material and a major consumer of void (landfill) space [29]. Increasing emphasis is now being placed on the minimisation of construction waste, with financial incentives such as the Landfill and Aggregates Levies operating in the UK. Stainless steel possesses a combination of high residual value (due to the alloy content) and excellent durability, lending itself to widespread re-use and recycling, bringing practical, financial and environmental advantages. Re-melting scrap using the electric arc process is the dominant means of production of stainless steel.

Whole-life costing

Cost comparisons made on the basis of the initial material expense of structural components do not reflect the true cost implications of a chosen structural material. A more appropriate analysis would include the additional immediate costs, such as corrosion protection and fire protection, and the longer term costs associated with maintenance and decommissioning.

A study conducted by the Steel Construction Institute [30] compared life-cycle costs of offshore structures made from carbon steel, aluminium and stainless steel. Consideration was given to initial material costs, maintenance and corrosion, production losses during maintenance, fire resistance and other potential cost savings. The study concluded that the use of both aluminium and stainless steel result in significant life-cycle cost savings as compared to carbon steel. Furthermore the combined economic and fire safety benefits that stainless steels offered were unequalled by the alternative materials.

Structural design

General

Historically stainless steel design rules have been based on assumed analogies with carbon steel behaviour, with modifications made where necessary to fit in with test results. More recently greater recognition has been given to the particular properties that stainless steel exhibits, allowing the generation of more efficient structural design rules. An overview of the provisions of the principal stainless steel design codes (European, US and Australia/New Zealand) was reported by Baddoo [31], whilst a more detailed comparison of their codified formulations with test results has also be prepared [32].

Design standards

The earliest dedicated stainless steel structural design Standard was published by the American Iron and Steel Institute (AISI) in 1968 as the *Specification for the Design of Light Gauge Cold-formed*

Stainless Steel Structural Members. The design rules were based primarily on the work carried out at Cornell University [33]. With an improved understanding of the structural behaviour of stainless steel and an increased availability of test results [34], a revised version of the Standard was published in 1974 [35]. Further research enabled the development of the American Society of Civil Engineers (ASCE) structural stainless steel design Standard, first published in 1991 and more recently in 2002 [36], which effectively superseded the AISI Standard in North America. Background and commentary to the ASCE Standards were reported [37].

In 1988, a joint industry project, managed by the Steel Construction Institute, was undertaken to develop recommendations for the design of stainless steel structures in Europe. The design rules were published by Euro Inox in 1994 as the *Design Manual for Structural Stainless Steel* [38]. Derived from the same material, the *Concise Guide to the Structural Design of Stainless Steel* (aimed at the UK market and utilising BS 5950 terminology), was published by the Steel Construction Institute [39]. In 2002, a second edition of the Euro Inox design manual was released [5].

The current European design (pre)standard for stainless steel structures, ENV 1993-1-4 [4] was introduced in 1996. ENV 1993-1-4 forms Part 1.4 of Eurocode 3: Design of steel structures, and contains supplementary rules for stainless steels. Its present status is that of a European prestandard, with conversion to a full European Standard (EN 1993-1-4) currently underway.

In 1995, the Japanese stainless steel structural design Standard was issued [40]; it is only available in Japanese and is focussed on the design of fabricated (welded) sections. Based largely on the Canadian design Standard for cold-formed carbon steel structures, the South African structural stainless steel Standard was published in 1997 [41]. Most recently, in 2001, the Australia/New

Zealand design Standard for cold-formed stainless steel structures [42] was issued. Background to the development of the Australia/New Zealand design Standard has also been described [43].

The following sub-sections outline and review various aspects of the structural design provisions of the European (EN(V) 1993-1-4), US (SEI/ASCE 8-02) and Australia/New Zealand (AS/NZS 4673) Standards, with an emphasis on the European Standard. In general, the design expressions are not provided as these are readily accessible in the appropriate design Standards.

Material strength and stiffness

The material properties of stainless steel vary with chemical composition and heat treatment (i.e. grade), product type, level of cold-worked, material thickness, direction of rolling (i.e. longitudinal or transverse), and direction of loading (i.e. tension or compression). Although some material Standards simplify matters by grouping cases with similar properties, there remains a wide range of values. The key material properties for two commonly adopted austenitic grades (EN 1.4301 and 1.4401), as provided by the European [4, 44], US [36] and Australia/New Zealand [42] Standards, have been summarised [31].

This paragraph gives an overview of the properties (modulus of elasticity E_0 and minimum specified yield strength f_y, taken as the 0.2% proof strength $\sigma_{0.2}$) for grades EN 1.4301 and 1.4401 in the annealed condition. For the modulus of elasticity, the European Standard EN 10088-2 [44] gives a value of 200000 N/mm^2, whilst the US and Australia/New Zealand Standards provide a lower value of 193100 N/mm^2. For minimum yield strength, the European Standard specifies 230 N/mm^2 (for cold-rolled strip of thickness less than 6 mm) and 210 N/mm^2 (for hot-rolled strip of thickness less than 12 mm) for grade EN 1.4301, and 240 N/mm^2 (for cold-rolled strip of thickness less than 6 mm) and 220 N/mm^2 (for hot-rolled strip of thickness less than 12 mm) for grade EN 1.4401, with no variation for anisotropy or non-symmetry of stress-strain response. The US and Australia/New Zealand Standards do account for these effects, with minimum yield strengths for the two grades ranging between 193.1 N/mm^2 and 206.9 N/mm^2, depending on the material orientation and direction of loading.

Cross-section design

The design of stainless steel cross-sections follows the familiar carbon steel approach, utilising the concepts of cross-section classification and, for slender elements susceptible to local buckling, the effective width method. For the calculation of effective widths, the European guidance given in ENV 1993-1-4 was aligned with that given in the equivalent carbon steel parts (Part 1.1 for hot-rolled sections and Part 1.3 for cold-formed sections). The US Specification adopted the ENV 1993-1-4 method for stiffened elements and that provided by the AISI Specification for cold-formed carbon steel for outstand elements [45]. The Australia/New Zealand Standard follows the US provisions.

The Euro Inox Design Manual for Structural Stainless Steel [5] recommends a more conservative approach for the calculation of effective widths. The effective width reduction factors take account of whether the elements are internal or external, and whether the element is welded or cold-formed. It is envisaged that the more conservative approach of the Euro Inox Design Manual will be adopted in Eurocode 3 Part 1.4 upon conversion from the ENV status. None of the current codified methods make explicit account for the effect of gradual yielding in the calculation of effective widths.

Member design

The behaviour of stainless steel members differs from that of carbon steel members due to the gradual yielding nature of the material stress-strain curve and variation in other characteristics such as the level of geometric imperfections and residual stresses. Geometric imperfections are generally lower in stainless steel products than equivalent carbon steel products because of tighter controls in the production process to limit the adverse effects of out-of-flatness on aesthetics. Initial analyses of measurements of geometric imperfections in structural stainless steel hollow sections [46] have supported this assertion. Residual stresses have been measured in cold-formed sections [21] and welded sections [47] and found to be of similar magnitude to those observed in carbon steel members.

The European provisions for stainless steel member design mirror those for carbon steel. The basic formulations are the same, though differences exist in the selection of the imperfection parameter α and the non-dimensional limiting slenderness $\bar{\lambda}_0$ (the plateau length), both of which effectively define the shape of the buckling curves. The buckling curves have been calibrated against all available stainless steel test data to provide a suitably conservative fit for design purposes. For simplicity (to avoid the need for iteration) and consistency with the carbon steel approach, no explicit allowance is made for the effect of gradual material yielding in the member buckling formulations. In addition to providing for the flexural buckling of columns and the lateral-torsional buckling of beams, guidance is also given for design against torsional and torsional-flexural buckling of compression members (by reference to Eurocode 3 Part 1.3). Since stainless steel structural members are generally cold-formed (i.e. relatively thin material) and are often open-sections (i.e. low torsional stiffness), susceptibility to these modes of failure should be checked.

The US provisions for stainless steel member design follow the AISI recommendations for carbon steel [45], except, to account for the non-linear (gradual yielding) stress-strain response, the tangent modulus E_t is used in place of the usual initial modulus E_0 in the buckling formulations. Additionally, for buckling modes with torsional components (lateral torsional buckling of beams and torsional and torsional-flexural buckling of columns), the initial shear modulus G_0 is replaced by the tangent shear modulus G_t. The non-linear stress-strain behaviour is described by the basic Ramberg-Osgood expression (Equation 1), and gradient of this curve at any stress level (i.e. the tangent modulus) may be determined through Equation 3.

$$E_t = \frac{\sigma_{0.2} E_0}{\sigma_{0.2} + 0.002 n E_0 \left(\frac{\sigma}{\sigma_{0.2}} \right)^{n-1}} \tag{3}$$

where n is the Ramberg-Osgood strain hardening exponent, and E_0 and E_t may be replaced by G_0 and G_t respectively in shear. Since the tangent modulus is dependent upon the buckling stress level, the US member design procedure is necessarily iterative.

The Australia/New Zealand Standard adopts the US recommendations for the design of beams and columns against member buckling. It also provides an additional method for the design of columns. The method utilises the familiar Perry formulation and adopts sophisticated imperfection factors derived on the basis of numerical modelling of imperfect columns.

A comparison between the flexural buckling curves of the European, US and Australia/New Zealand design Standards is shown in Figure 6 for f_y = 210 N/mm^2 and E = 200000 N/mm^2, where χ is the buckling reduction factor and member slenderness is given as length, L divided by radius of gyration, i. For the US and Australia/ New Zealand buckling expressions, the Ramberg-Osgood parameter n has been taken as 4.0 (which applies to grades 1.4301 and 1.4401 in longitudinal compression). The comparison shows that the Eurocode curve for welded sections gives the most severe reductions, but generally indicates relatively small deviation between the design Standards.

For stainless steel members subjected to combined axial load plus bending (beam-columns), each of the Standards under consideration adopts their respective approaches for carbon steel, with the Australia/New Zealand Standard implementing the US provisions.

Serviceability

For the determination of deflections in stainless steel flexural members, account must be taken of the non-linear stress-strain characteristics of the material; simply assuming the initial tangent modulus E_0 will result in an under-estimation of deflections. The European, US and Australia/New Zealand design Standards all adopt essentially the same treatment, whereby deflections are calculated based on an effective section (for slender Class 4 cross-sections) and a reduced modulus of elasticity. In all Standards the reduced modulus of elasticity is taken as the average of the secant moduli in tension and compression corresponding to the maximum serviceability stresses that occur along the member length (Equation 4).

$$E_{s,ser} = \frac{E_{st} + E_{sc}}{2} \tag{4}$$

where $E_{s,ser}$ is the secant modulus at the serviceability limit state, and E_{st} and E_{sc} are the secant moduli in tension and compression corresponding to the maximum serviceability stresses that occur along the member length. The secant modulus for a given stress level may be approximated from the Ramberg-Osgood expression (Equation 1) through Equation 5.

$$E_{s,i} = \frac{E_0}{1 + 0.002\dfrac{E_0}{\sigma_{ser,i}}\left(\dfrac{\sigma_{ser,i}}{\sigma_{0.2}}\right)^n} \qquad (5)$$

where $E_{s,i}$ is the secant modulus, with the subscript i referring to either tension or compression, and $\sigma_{ser,i}$ is the maximum serviceability stress in tension or compression. Clearly, calculating deflections based on the secant modulus at the most highly stressed section of a member will lead to an over-estimation of deflections, with the level of over-estimation dependent upon the distribution of bending moments along the member length. Comparisons between measured deflections from tests on stainless steel flexural members and predicted deflections from design Standards and other more sophisticated techniques (that account for variation in stress along the member length) have been made by [14] and [48].

Joints

Structural stainless steel joints may utilise welding, bolting or other mechanical fasteners. Basic design philosophy is no different from that for carbon steel joints, and the high ductility that stainless steel offers (particularly the austenitic grades) should be beneficial. There are however a number of general design aspects that require consideration, in particular to minimise the risk of corrosion; problems may be experienced where crevices exist, where there is dissimilar metal contact inducing galvanic corrosion (e.g. joints comprising both stainless steel and carbon steel components) and in the heat affected zone resulting from welding. General recommendations for stainless steel joint design may be found in [5].

The common grades of stainless steel are readily weldable; the austenitic grades especially, can be welded with ease, and since there is no change in metallurgical structure with temperature, the weld material and surrounding zone should remain tough and ductile. As with ordinary carbon steel, stainless steel grades with a low carbon (equivalent) content are desirable for welding (such as EN 1.4306 (AISI 304L) and EN 1.4404 (AISI 316L)), though these grades generally possess slightly lower strengths. More detailed guidance on welding of stainless steels is available in [1] and [49].

The structural behaviour of stainless steel joints is similar to that of carbon steel joints, and this is reflected in design guidance. Design rules are provided in each of the three design Standards under consideration, with slight variations from their corresponding carbon steel recommendations. The European guidance for stainless steel joints adopts the rules of Eurocode 3 Part 1.8 [50], subject to some minor modifications given in Part 1.4.

Fire design

The elevated temperature physical properties of stainless steel differ significantly from those of carbon steel, as discussed earlier; material strength and stiffness reduction factors are compared with those of carbon steel in Figures 4 and 5, respectively. The European provisions for the design of stainless steel members in fire largely follow the carbon steel rules, with the primary differences being in the material properties. These properties are due to be incorporated into an Annex of EN 1993-1-2 [51] (Eurocode 3: Part 1.2 – Structural fire design) to extend the scope of this document to the structural design of stainless steel in fire. Neither the US nor the Australia/New Zealand structural stainless steel design Standard currently cover fire design, though some background and guidance is provided as an Informative Annex in the Australia/New Zealand Standard.

Fatigue

The fatigue resistance of stainless steel has recently been shown to be comparable to that of carbon steel [24], with indications of superior fatigue performance in many configurations. Hence, the European prestandard ENV 1993-1-4 states that the design approach for carbon steel may be directly applied to stainless steel. Upon completion, European guidance for the design of steel (and stainless steel) structures subjected to fatigue loading will be contained in EN 1993-1-9 [52]. No guidance on the assessment of fatigue strength of stainless steel structures is included in the US Standard. As with the European Standard, the Australia/New Zealand Standard recommends use of the equivalent carbon steel approach, given in AS 4100 [53], though with some limitations.

A new approach

An important step towards enhancing the understanding and use of stainless steel in structures has been the development and publication of design guidance, including the European [4], US [36] and Australia/New Zealand [42] Standards. However, although the US and Australia/New Zealand Standards take account of the non-linear material behaviour below the 0.2% proof stress in the determination of member buckling resistances, none of the existing design methods take account of the non-linear material behaviour on a cross-sectional level; the consequence of this is inaccurate prediction of cross-section behaviour where buckling occurs below the 0.2% proof stress and inefficient prediction of cross-section behaviour where buckling occurs above the 0.2% proof stress (due to neglection of the considerable strain hardening that stainless steel exhibits). Essentially therefore, the existing design methods utilise a simplified elastic, perfectly-plastic material model for the determination of cross-section resistance (upon which member resistances subsequently impinge). This model is acceptable for carbon steel that exhibits a sharply defined yield point, followed by a plastic yield plateau. For stainless steel, though, where there is no sharply defined yield point and substantial strain hardening occurs, this model leads to overly conservative designs.

The existing structural stainless steel design codes place cross-sections into discrete behavioural classes on the basis of individual element slendernesses; the well known procedure of cross-section classification. Eurocode 3 defines four discrete behavioural classes of cross-sections. Cross-sections with very high deformation capacity are classified as Class 1. They are fully effective under pure compression and are capable of reaching and maintaining their full plastic moment in bending. Class 2 cross-sections have a somewhat lower deformation capacity, but are also fully effective in pure compression and capable of reaching their full plastic moment in bending. Class 3 cross-sections are fully effective in pure compression, but local buckling prevents attainment of the full plastic moment in bending. Bending moment resistance is therefore limited to the yield moment. For Class 4 cross-sections, local buckling occurs in the elastic range. An effective cross-section is defined based on the width-to-thickness ratios of individual plate elements, and this is used to determine the cross-sectional resistance.

In view of the continuous nature of the stainless steel stress-strain curve, it seems rational that a continuous, rather than a discretised system of design should be adopted. A new design method has been developed [13, 32] that replaces the discrete behavioural classes by a single numerical value that is a measure of the deformation capacity of the cross-section. The deformation capacity is based upon the slenderness of individual plate elements and the interaction between elements within the cross-section. The relationship between cross-section slenderness and cross-section deformation capacity has been derived on the basis of stub column tests, including those performed as part of recent significant testing programmes [17, 54, 55, 56].

For design purposes, cross-section resistances are determined using a local buckling strength derived from the cross-section deformation capacity, in conjunction with an accurate material model appropriate for stainless steels. The adopted material model is the compound Ramberg-Osgood formulation given by Equation 2, and it enables stresses greater than the 0.2% proof stress to be exploited in design. Member strengths are determined using the local buckling strength (raised to a power) in combination with overall buckling curves. For bending resistance, the concept of a generalised shape factor, originally devised by [57], into which material as well as geometric properties of a cross-section are incorporated, is used. The resistances of members subjected to a combination of axial load plus bending moments are determined through an interaction of the component effects.

The new design method utilises accurate material modelling, accounts for element interaction within cross-sections and provides a continuous measure of section deformation capacity (in place of the current discretised system of section classification). The method has been shown to provide average member strength enhancements of around 20% over existing design methods, whilst for stocky cross-sections enhancements in member bending strengths of over 50% have been achieved [13]. Further development to expand the scope of the design method is currently underway, and it is envisaged that the new approach could be incorporated as an alternative method in future revisions of Eurocode 3.

Conclusions

Significant advances related to the use of stainless steel in structures have been made in recent years, including the publication of a number of major structural stainless steel design Standards. This paper provides of overview of the provisions of these Standards and a review of the material and recent research activities upon which the documents have been based. Factors influencing stainless steel as a material choice for structural engineering applications have also been discussed in the context of recent advances. Although the initial material cost of stainless steel structural products is about four times that of equivalent carbon steel products, it has been explained that comparison of costs on a more holistic basis reveals a far lesser discrepancy.

The paper describes that, unsurprisingly, many aspects of the design of stainless steel closely follow those of carbon steel, though there is sufficient diversity in physical properties to require separate structural design treatment; it is the differences in structural design treatment that have been the focus herein.

Acknowledgements

The author would like to thank Professor David Nethercot of Imperial College London, Nancy Baddoo and Dr Bassam Burgan of the Steel Construction Institute and Dr David Dulieu of Outokumpu for their support on recent structural stainless steel projects.

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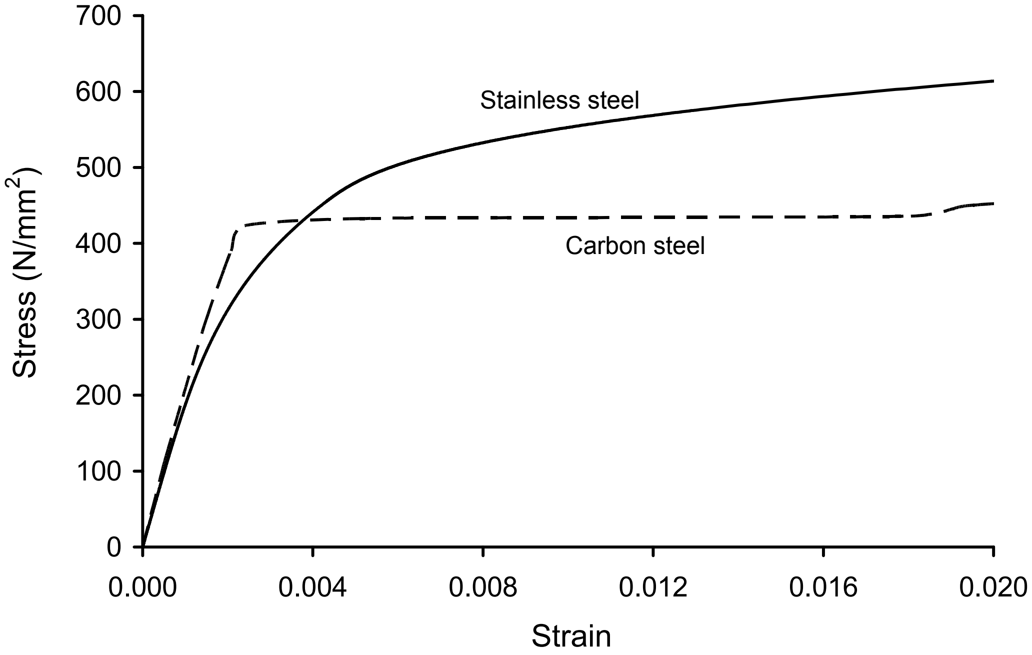

Figure 1: Indicative carbon steel and stainless steel material σ–ε behaviour

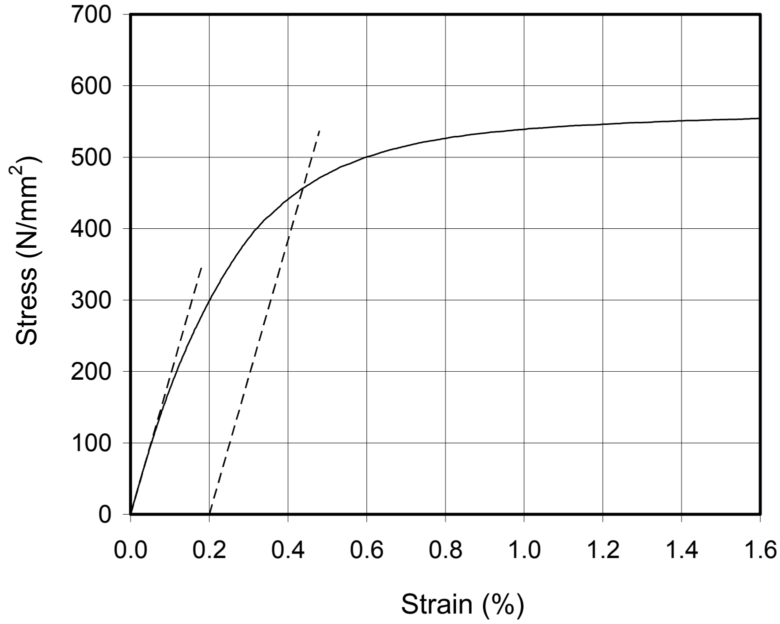

Figure 2: Definition of ‘equivalent’ yield stress using the 0.2% proof stress

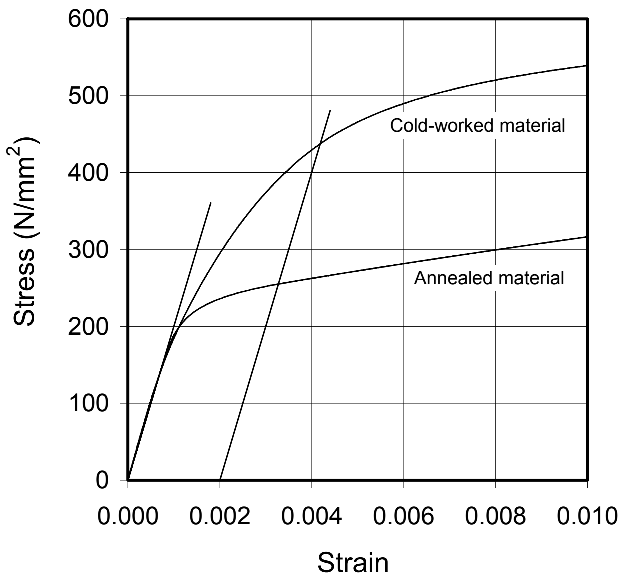

Figure 3: Stress-strain behaviour of annealed and cold-work material

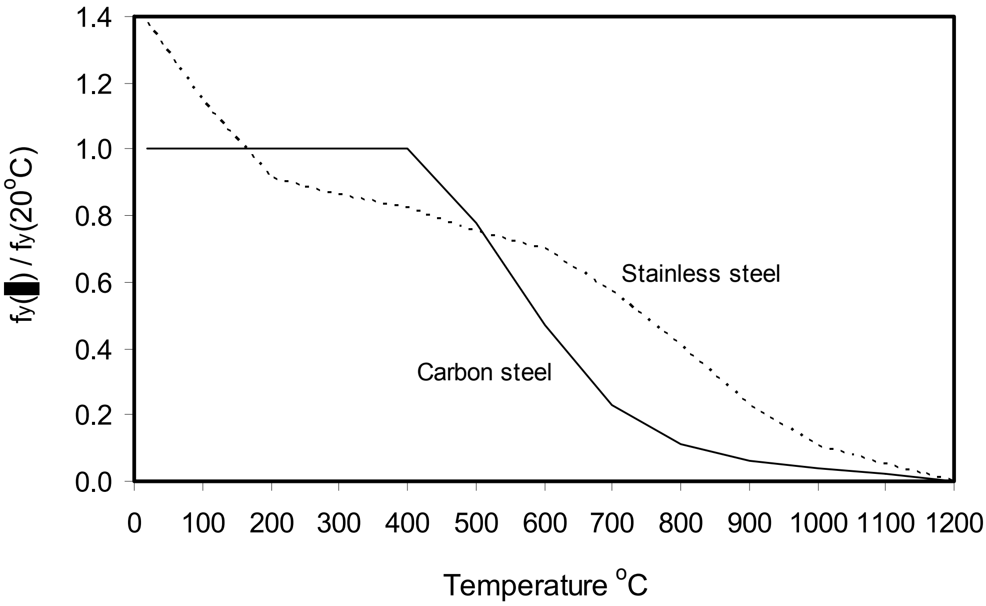

Figure 4: Strength retention of stainless steel and carbon steel at elevated temperatures

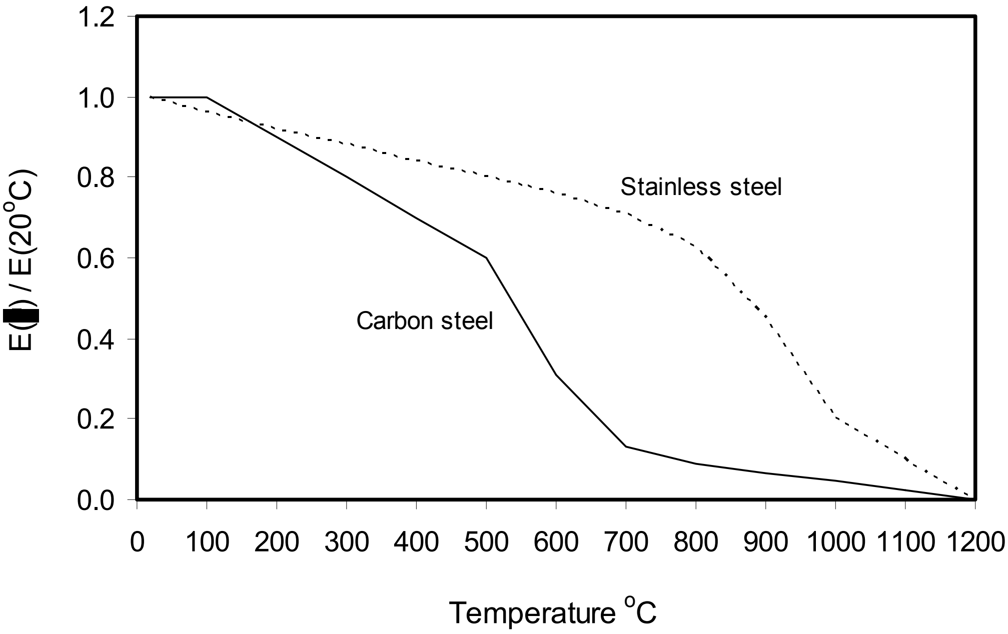

Figure 5: Stiffness retention of stainless steel and carbon steel at elevated temperatures

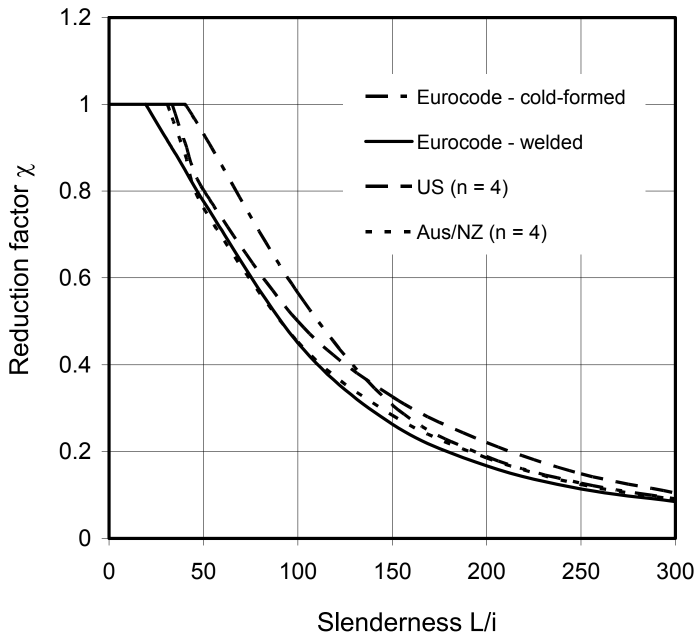

Figure 6: Comparison of the European, US and Australia/New Zealand flexural buckling curves

Table 1: Chemical compositions for selected stainless steel grades

Chemical composition (% by mass)			
Element	Steel Designation (Number)		
	1.4301 (304)	1.4401 (316)	1.4462 (2205)
Carbon (C)	≤ 0.07	≤ 0.07	≤ 0.030
Chromium (Cr)	17.00 to 19.50	16.50 to 18.50	21.00 to 23.00
Nickel (Ni)	8.00 to 10.50	10.00 to 13.00	4.50 to 6.50
Molybdenum (Mo)	-	2.00 to 2.50	2.50 to 3.50
Manganese (Mn)	≤ 2.00	≤ 2.00	≤ 2.00
Silicon (Si)	≤ 1.00	≤ 1.00	≤ 1.00
Phosphorus (P)	≤ 0.045	≤ 0.045	≤ 0.035
Sulphur (S)	≤ 0.015	≤ 0.015	≤ 0.015
Nitrogen (N)	≤ 0.11	≤ 0.11	0.10 to 0.22
Titanium (Ti)	5×C to 0.70	5×C to 0.70	-
Tungsten (W)	-	-	0.50 to 1.00