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AESTHETICS, ECONOMICS AND DESIGN OF STAINLESS STEEL STRUCTURES

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Abstract

The use of stainless steel in structural and architectural applications is growing due, in part, to the material's attractive appearance, corrosion resistance, ease of maintenance, low life cycle costs and fire resistance, alongside improved and more widespread design guidance and enhanced product availability. This paper explores the aesthetics, economics and design of stainless steel structures, highlighting recent applications in practice and recent advances in research. Increasingly, the construction industry, in common with most other industries, is expected to consider the longer term economic and environmental implications of material specification. Whilst structural carbon steel generally offers the most economic solution based on initial material costs, alternative metallic materials such as aluminium and stainless steel offer long-term benefits and associated cost savings. Life-cycle cost analyses of carbon steel and stainless steel employed in a range of structural applications are summarized herein. 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. Current design rules for stainless steel structures and deficiencies thereof are described in this paper.

Keywords: Aesthetics, cold-work, deformation capacity, design, economics, stainless steel,

structures

1. INTRODUCTION

The elegance of metallic structures has long been a feature of the construction industry, and whilst carbon steel remains the predominant material choice, there is an increasing use of alternative metallic materials, such as stainless steel, to meet rising demands on the durability, efficiency and sustainability of structures. The greatest advantage that stainless steel offers over other structural materials is its durability – appropriately specified, stainless steel requires no corrosion protection and minimal maintenance, leading to low life-cycle costs, reduced environmental impact and considerably extended design lives. Further benefits include high ductility, impact resistance and fire resistance, though it is the aesthetic appeal of stainless steel that has often been a central factor in its specification. The principal drawback to stainless steel is the material cost – approximately four times that of carbon steel. A review of the use of stainless steel in structures has been presented [1] and a number of case studies have been collated [2].

Significant progress has been made in recent years in the development of structural stainless steel design guidance and in the enhancement of product availability. 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 explores the aesthetics, economics and design of stainless steel structures, highlighting recent applications in practice and recent advances in research.

2. STRUCTURAL APPLICATIONS AND AESTETICS

Historically, the aesthetics of stainless steel has been an important factor in its specification for structural and architectural applications. Consequently, many existing examples of stainless steel structures 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.

Following its invention in 1912, the first significant application of stainless steel in construction was the upper facade of the Chrysler Building in New York, completed in 1930 (see Figure 1). This building now serves to exemplify the aesthetics and longevity of the material which, despite the aggressive atmosphere and proximity to the ocean, has shown no deterioration with time and remains bright and clean.

In the 1920s and 1930s, the influential Swiss architect Le Corbusier set out his vision for a modern city – central to his vision was to embrace new technology and new materials. Although only to be truly realised some 30 years later, Le Corbusier's ideas [3] to consider buildings as machines heightened the eras drive towards creating buildings that communicated their efficiency, function and cleanliness, in contrast to the Victorian precedents. Built between 1971 and 1977, Richard Rogers' and Renzo Piano's Pompidou Centre in Paris took modernist ideas and industrial design to spectacular extremes. With the aim of providing the maximum interior space and greatest internal flexibility, the structure and services were all located external to the building, celebrating rather than concealing their presence and purpose. The main structural material of the Pompidou Centre is steel (see Figure 2), though stainless steel is also employed as a cladding material.

Following on from the Pompidou Centre, Richard Rogers' next landmark project was the Lloyds Building, situated in the City of London and completed in 1986. Once again, the services and stairs were located on the outside of the building (Figure 3). The main structure of the Lloyds Buildings is reinforced concrete, but stainless steel plays a prominent role in the external architecture. In addition to the cladding of the main stair and technical units, stainless steel also features in the handrail and balustrade systems (Figure 4) and in the main entrance canopy (Figure 5).

General details and discussion of the architecture of both the Pompidou Centre and the Lloyds Building, along with a number of other projects that incorporate stainless steel (including the Grande Arche de la Défense and the Grand Louvre in Paris) may be found in [4]. Stainless steel is frequently adopted for handrails, and in combination with glass for partitioning due to its aesthetic appeal, high durability and ease of cleaning (see Figure 6).

The surface finish of structural and architectural products is key to the aesthetics of stainless steel structures, whilst fundamental to the preservation of the surface finish is corrosion resistance. Upon exposure to air, stainless steel reacts with the oxygen to form a protective oxide layer (chromium oxide). This oxide layer adheres to the surface of the material and prevents the occurrence of further oxidation or corrosion. When damaged, provided oxygen is present, this oxide layer very rapidly reforms. Carbon steel also oxidises to form iron oxide. However, unlike chromium oxide, iron oxide does not adhere to the material, but rather occupies a larger volume and becomes detached from the surface, exposing un-corroded material to further oxidation. In certain conditions, stainless steel can be susceptible to corrosion. Aggressive environments, where particular care needs to be taken to select appropriate material grades to avoid severe corrosion, include strongly acidic or alkaline conditions; sea water, for example, is a weak chloride solution. General guidance on the corrosion of stainless steel is available [5].

A wide range of surface finishes of stainless steel is available. These may be divided into two basic groups: standard mill finishes and finishes obtained by polishing. Standard mill finishes are the basic supply conditions for all stainless steel hot-rolled or cold-rolled flat products. For architectural and building applications, surface finish designations 1D, 2D, 2B and 2R are the most important [6]. The 1D finish is hot-rolled, annealed and pickled (to remove mill scale) to form a slightly coarse surface with low reflectivity – this finish is acceptable for non-decorative structural applications. The 1D surface finish may be refined by cold-rolling, heat treating and pickling to form a low reflective matt surface designated 2D. A final light rolling using highly polished rollers will convert a 2D finish into a 2B finish. The 2B finish is smooth and reflective and is the most widely used. By bright annealing in an oxygen-free atmosphere following cold-rolling using polished rolls, a highly reflective 2R finish may be achieved. Further details of the described surface finishes, together with additional finishes and effects (including patterned finishes, electro-polished finishes and coloured finishes) may be found in [6]. The different surface finishes available in stainless steel allow the designer the opportunity to modulate how the structural presence is felt. High shines, for example, allow the structure to dissipate into reflections of light held in the surrounding space, and with the reflections continuously capturing a changing environment, a sense of uncontained space is promoted. Stainless steel can also be effectively used in combination with glass creating a feeling of immateriality to divide spaces physically but not visually.

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. 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 a continuous process 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.

To date, the use of stainless steel in load bearing applications has been less extensive than its general use in architecture and amongst other industries. More widespread use has been partly inhibited by a lack of availability of design guidance and structural products, and limited knowledge amongst structural engineers regarding the specification, properties and benefits of the material. However, following significant recent research activity there is now a range of design guidance for stainless steel structures, including dedicated provisions in Europe, North America, Australian/ New Zealand and Japan. Structural applications of stainless steel are consequently becoming increasingly frequent. Recent examples are shown in Figures 7 to 11. The Grande Arche de la Défense in Paris, completed in 1989, incorporates a 91 m high external stainless steel lift structure (Figure 7). The structural members are grade 1.4462 (duplex stainless steel) tubular cross-sections varying from 60 mm to 244 mm in diameter. Figure 8 shows an external stainless steel lateral bracing system and façade supporting structure on the nine-storey Sanomatalo Building in Helsinki. The project was completed in 1999, utilises hot-rolled and cold-formed sections and includes welded and bolted details (see Figure 9).

A number of examples of the use of stainless steel for the primary structural elements of bridges have also recently emerged, including road bridges in Siena and Menorca and footbridges in London, Paris, Stockholm, and York. The road bridge in Menorca, Spain has an overall length of 55 m and a width of 13 m, carrying two lanes of traffic. The structural system comprises two parallel duplex stainless steel arches, longitudinal beams and transverse beams that act compositely with a reinforced concrete deck. A full description of the Menorca road bridge, including details of the construction may be found in [10]. The Millennium footbridge in York (Figure 10) incorporates an 80 m duplex stainless steel inclined arch and was completed in 2001. Further details of the York Millennium Bridge and numerous other examples of stainless steel footbridges may be found in [11].

Figures 7 to 10 all show examples of the use of stainless steel in exposed structural applications, where the form and function of the structure are clearly visible. Stainless steel, with its natural corrosion resistance, appealing surface finishes and good fire resistance clearly lends itself to such expressive architecture. Exposure of the natural surface of the material also generates a non-artificial environment where the structure can be made to feel like a sculptural part of the space not just a functional necessity, which is boxed or painted to reduce its impact or excuse its existence. The ability of the exposed finish to remain constant over time presents a sense of permanence and quality.

3. ECONOMICS AND SUSTAINABILITY

Within the construction industry, material selection has traditionally been based largely on initial material cost leading to the dominance of structural carbon steel over other metallic materials. Familiarity and ease of design and construction using carbon steel, together with a comprehensive range of structural products, have also contributed. The high cost of stainless steel (approximately four times that of ordinary structural carbon steel) is a clear and significant disincentive to its application. However, growing pressure on the construction industry to consider the longer term financial and environmental implications of projects is encouraging a more holistic approach. Thus, materials such as stainless steel with higher initial costs, but which offer cost savings over the life cycle of a structure, are gaining increasing recognition.

Recent studies [12,13] have considered the relative life cycle costs of stainless steel and carbon steel structures employed in building, bridge and offshore applications. These applications differ in scale, life time expectancy, environmental corrosivity, maintenance requirements, cost of disrupted use and in the manner in which they are funded. The life cycle cost calculations incorporated initial material costs and the costs associated with initial corrosion and fire protection taken at their present values, and maintenance costs, end of life costs and the residual value of the structure discounted to their present value by means of a discount rate. The studies found that, on an initial cost basis, carbon steel consistently offered the most competitive solution. However, although carbon steel offered the most competitive life cycle solution for the building, stainless steel was found to be more economic over the life-cycle of both the bridge and offshore structures. Overall, it was concluded that on a whole-life basis stainless steel may offer more competitive solutions than carbon steel for bridges, exposed areas of building structures and offshore structures.

A further consideration is that the construction industry is a major producer of waste material and a major consumer of void (landfill) space. 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.

The high initial material cost of stainless steel is partly due to the relatively low volume of production, but is primarily linked to the cost of the constituent alloying elements (principally chromium and nickel), and it is not anticipated that the relative material costs of stainless steel and carbon steel will alter significantly in the foreseeable future. Therefore, in addition to exploiting the favourable properties of stainless steel, there is also a clear need to ensure that stainless steel is utilised efficiently and to develop the availability and diversity of the current product range. Notable recent advances include the development of a deformation based approach to the design of stainless steel elements which harness the strain hardening characteristics of the material [14,15], and the generation of structural design guidance for high strength cold-formed stainless steel [16,17].

4. STRUCTURAL DESIGN

Significant progress has been made in recent years towards the development of comprehensive and efficient structural design guidance for stainless steel. 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. With an increased availability of test results, a revised version of the Standard was published in 1974. 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 [18], which effectively superseded the AISI Standard in North America. In Europe, design rules were first published by Euro Inox in 1994 as the Design Manual for Structural Stainless Steel. In 2002, a second edition of the Design Manual was released [19]. Part 1.4 of Eurocode 3 is also dedicated to the design of stainless steel structures; the pre-standard, ENV 1993-1-4 was published in 1996, whilst the final EN 1993-1-4 [20] is due to be published in 2006. In 1995, the first Japanese stainless steel structural design Standard was issued; 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. Most recently, in 2001, the Australia/New Zealand design Standard for cold-formed stainless steel structures [21] was issued.

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). This variation is recognised in codes, though some simplifications are employed to facilitate 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 EN 1993-1-4 refers to the equivalent carbon steel parts (Part 1.1 for hot-rolled sections and Part 1.3 for cold-formed sections). 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. 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, 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 well known Ramberg-Osgood expression. Since the tangent modulus is dependent upon the buckling stress level, the US member design procedure is necessarily iterative.

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 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.

Although a significant step forward, current design methods do no adequately allow for the rounded nature of the stress-strain curve of stainless steel and the considerable strain-hardening. A new, approach has been developed that replaces the current discretised system of cross-section classification based on bi-linear material assumptions with a continuous, deformation capacity based measure of resistance. The new approach utilises an accurate material description and yields average increases in member resistance of around 20% over current design methods. The method has been verified on the basis of existing test data and numerical data and is detailed in [14] and [15].

5. CONCLUSIONS

The aesthetics of stainless steel has been an important factor in its specification in the construction industry. Its appeal, exemplified in landmark structures such as the Chrysler Building in New York, the Lloyds Building in London and the Grande Arche in Paris, is principally associated with the surface finish of the material, but also its ability to retain this finish over time. Whilst most existing applications of stainless steel in construction have been of a primarily architectural nature, use in load-bearing applications is growing. In particular, a range of examples of the use of stainless steel in road bridges and pedestrian bridges has recently emerged.

The initial material cost of stainless steel is about four times that of ordinary structural carbon steel – this represents the most significant factor in inhibiting more widespread use, though limited design guidance and a lack of familiarity amongst structural engineers and fabricators have also contributed. Significant progress has been made in recent years in the development of design guidance and verified structural design rules are now widely available, although further improvements in efficiency are necessary. By considering the additional benefits of stainless steel over carbon steel, including corrosion resistance, durability, ductility, fire resistance, residual value and sustainability, structural application of the material becomes more economically and environmentally appealing.

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Figure 1: Chrysler Building, New York

Figure 2: Pompidou Centre, Paris

Figure 3: Services and stairs located on the exterior of the Lloyds Building in London

Figure 4: Stainless steel cladding, handrails and balustrade systems (Lloyds Building, London)

Figure 5: Stainless steel entrance canopy of Lloyds Building, London

Figure 6: Stainless steel partitions and handrails at Barcelona airport

Figure 7: Grande Arche de la Défense, Paris

Figure 8: Sanomatalo Building, Helsinki

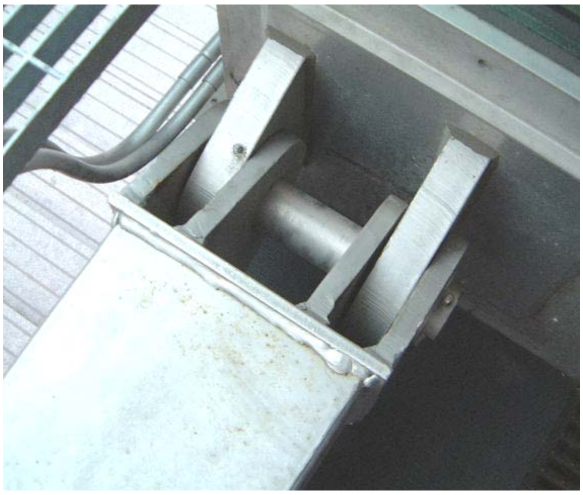

Figure 9: Connection detail in the
Sanomatalo Building, Helsinki

Figure 10: Millennium footbridge, York